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THE ECONOMIC POTENTIALS OF NATURAL GAS PRODUCTION STIMULATION BY NUCLEAR EXPLOSION

by

Klaus-Peter Heiss

ATOMIC ENERGY COMMISSION
UNITED STATES OF AMERICA

Prepared for
U. S. Atomic Energy Commission
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SPECIAL REPORT

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MATHEMATICA
Princeton, New Jersey

FOREWORD

Since the Plowshare Program was established in 1957 to investigate and develop peaceful uses for nuclear explosives, a large number and variety of applications have been suggested. As a result of the Plowshare research effort, many suggestions have been discarded for technical reasons while others have been more clearly identified as long-range possibilities requiring still more data and further development. Other ideas have now been sufficiently developed and offer enough promise to warrant the type of pilot-scale or prototype experiment needed to obtain precise information in an industrial framework.

By the time such an experiment is seriously considered and proposed, there is a need for some general economic appraisal of the potential value of the application. In the course of research some economic information is usually generated; however, for the most part, the AEC has relied primarily on government agencies responsible for resource development and on industry for information and general economic evaluations. As a result, this information and analysis is scattered throughout different reports, and appraisals have often been made on different bases and with different assumptions and resource information. Since a number of these applications are now approaching a commercial technology level, it seems timely and desirable to make some effort to collect this information, put it on as consistent a basis as possible, place it in the proper economic and resource perspective, and include enough relevant technical and cost information about nuclear explosions, their effects and associated operations, to permit a better and more detailed analysis from an economic point of view.

To these ends, Mathematica Incorporated of Princeton, New Jersey, was engaged to carry out this assignment. They have produced a series of reports covering the various areas of application for peaceful nuclear explosions and a general summary report. These reports are not intended to be definitive economic analyses, since sufficient data is still not available for such analysis. Rather, these studies are intended to serve as a beginning point and a means of identifying on a consistent basis the range of potential of the presently known, most promising applications. It is hoped that they will serve as a useful guide for future economic studies, especially by identifying key technical questions which affect the economics of the applications, such as whether the fractured area of oil shale surrounding the nuclear chimney can also be retorted. It is towards answering these key technical questions that much research and development, including the design of current experiments, is being devoted. Beyond the identification of key technical questions, these studies attempt to define the controlling economic parameters for the different applications, such as the diameter of explosives and concomitantly the cost of very deep drill holes for the gas production stimulation applications.

With the expectation that this information will be of general interest, as well as a guide for the research of those working in Plowshare, the AEC is pleased to make these reports available.

John S. Kelly, Director
Division of Peaceful
Nuclear Explosives

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INTRODUCTION

The present report describes the technical and economic potentials of gas stimulation by nuclear explosives. It is part of a larger study of Plowshare whose principal aim is to analyze, on the basis of all available technological information, the economic consequences which various Plowshare projects would entail. The present report shows that there exists a sufficiently firm body of information which will have to be enlarged and improved by experiments specifically related to gas stimulation to confirm the statement that gas stimulation can become one of the first technically and economically feasible applications of the peaceful uses of nuclear explosives.

From this study it appears that gas stimulation can be applied with profit in existing tight gas fields which can not be exploited with conventional techniques. The study further states that if the existing body of information is confirmed, the peaceful application of nuclear explosives would increase the United States recoverable natural gas resources by amounts greatly in excess of known supplies. Specifically, it appears that the increase would extend the present supply of gas by adding a supply of at least 18 years. The true figure might in fact exceed 55 years additional supplies, even allowing for a substantial annual increase in demand by the United States economy.

Chapter 1

PHENOMENOLOGY

The sequence of events in the case of gas stimulation by means of nuclear explosives is the same as that in all other underground nuclear explosions. A nuclear charge is emplaced, exploded, and after the explosion creates a cavity which then is presumed to collapse. The long range effects of the nuclear explosions are thus mainly the formation of a rubble chimney, the dimensions of which are determined by equations (1), (2) and (6) [34]. The radius of the chimney is a function of the yield of the explosive, the depth of burial, overburden pressure and a lithology factor which varies with the medium in which the charge is exploded [1, 5, 10, 247]:

$$R = \frac{C\,W^{1/3}}{(\rho\,h)^{1/4}} \qquad (1)^{*}$$

---

* Equation (1) is derived from the general equation which describes the results of 46 nuclear detonations in alluvium, granite, salt and tuff, that

$$R = 100\left[\frac{(\bar{\gamma}-1)\,P_v^{\frac{1}{\overset{+}{\gamma}}-1}\,W}{(\rho\,h)^{\frac{1}{\overset{+}{\gamma}}}}\right]^{1/3}$$

where $\bar{\gamma} - 1$ is a proportionality constant, P_v is the final rock vapor pressure and $\overset{+}{\gamma}$ is the adiabatic expansion coefficient. Assuming P_v and $\bar{\gamma}$ fixed and $\overset{+}{\gamma} = 4/3$ this expression reduces to (1), where C comprises all the constant terms [247].

The height of the chimney is generally expressed as a simple multiple of the chimney radius:

$$H = C_h R \tag{2}$$

where

R = Chimney radius in feet

H = Chimney height in feet

W = Yield in KT (10^{12} calories)

ρ = Overburden bulk density ($\approx$ 2.3 - 2.5)

h = Depth of burial in feet

C = Lithology factor, $\approx$ 325 in formations containing hydrogen (water)

C_h = Height factor, $\approx$ 5

The lithology factor in equation (1) is still more or less uncertain, as apparently C is a function of the medium in which the nuclear device is exploded and too few experiments have been made to allow a reliable inference for all possible media [34, p. 111]. C ranged from 261 (Hard hat) to 362 (Platte event), [247].* When water (hydrogen) is present, the C constant is apparently increased by about 15 to 25%.** The

---

* Earlier publications, e.g., [34, p. 124] mention a C value for Hard hat of 194 and for Platte of 269.

** G. H. Higgins and T. R. Butkovich pointed out [247] that by allowing for an adjustment in the adiabatic expansion coefficient for varying water content, the difference in C could be reduced from + 25% to + 15%. This treatment will improve predictions of cavity dimensions if water (hydrogen) is present [247, p. 5-6].

constant C depends on the concentration with which water (hydrogen) occurs. Though C in other media is around 270, it appears from present evidence that C in hydrogen-rich formations equals at least 325. The corresponding graphs are shown in Figures 1.1 and 1.2 for C < 270 [54].

Table 1.1--Predicted Effect of Nuclear Explosions in Sandstones Containing Hydrocarbons (C = 325) (in feet)

Yield	Depth of Burial		
50 KT	5,000	7,500	10,000
Radius of Chimney, R	115	103	96
Radius of Fractured Zone, R_f	461	413	384
Height of Chimney, H	576	516	480
Height of Fractured Zone, H_f	806	722	672
100 KT			
Radius, R	145	131	121
Radius of Fractured Zone, R_f	581	523	485
Height of Chimney, H	726	654	606
Height of Fractured Zone, H_f	1,016	916	848
200 KT			
Radius, R	182	164	154
Radius of Fractured Zone, R_f	730	658	602
Height of Chimney, H	912	822	768
Height of Fractured Zone, H_f	1,277	1,152	1,075

Based on equations (1), (2), (3), (4)

$C_h = 5$, $C_f = 7$, $C_r = 4$, $\rho = 2.20$ at 5000 feet

SOURCE: Bray, B.G., H. F. Coffer, C. F. Knutson, "Applications of Nuclear Explosives to Increase Effective Well Diameters," Engineering with Nuclear Explosives, Proceedings of the Third Plowshare Symposium, Livermore, California, April, 1964.

Table 1.2--Effect of Nuclear Explosions
Present Experience in Non-hydrocarbons
(C = 270)
(in feet)

Yield	Depth of Burial		
50 KT	5,000	7,500	10,000
Radius of Chimney, R	96	86	80
Radius of Fractured Zone, R_f	384	344	320
Height of Chimney, H	480	430	400
Height of Fractured Zone, H_f	672	602	560
100 KT			
Radius of Chimney, R	121	109	105
Radius of Fractured Zone, R_f	484	436	404
Height of Chimney, H	605	545	505
Height of Fractured Zone, H_f	847	763	707
200 KT			
Radius of Chimney, R	152	137	128
Radius of Fractured Zone, R_f	608	548	502
Height of Chimney, H	760	685	640
Height of Fractured Zone, H_f	1,064	960	896

Based on equations (1), (2), (3), (4)

$C_h = 5$, $C_f = 7$, $C_r = 4$, $\rho = 2.20$ at 5000 feet.

SOURCE: Bray, B.G., H. F. Coffer, C. F. Knutson, "Applications of Nuclear Explosives to Increase Effective Well Diameters," Engineering with Nuclear Explosives, Proceedings of the Third Plowshare Symposium, Livermore, California, April, 1964.

In addition to the chimney, a fracture zone is created, the parameters of which again may be measured as a multiple of the chimney radius [5], (and see Table 1.1) as expressed in equations (3) and (4):

$$H_f = C_f R \tag{3}$$

$$R_f = C_r R \tag{4}$$

Figure 1.1--Cavity Radius for Underground Nuclear Explosions

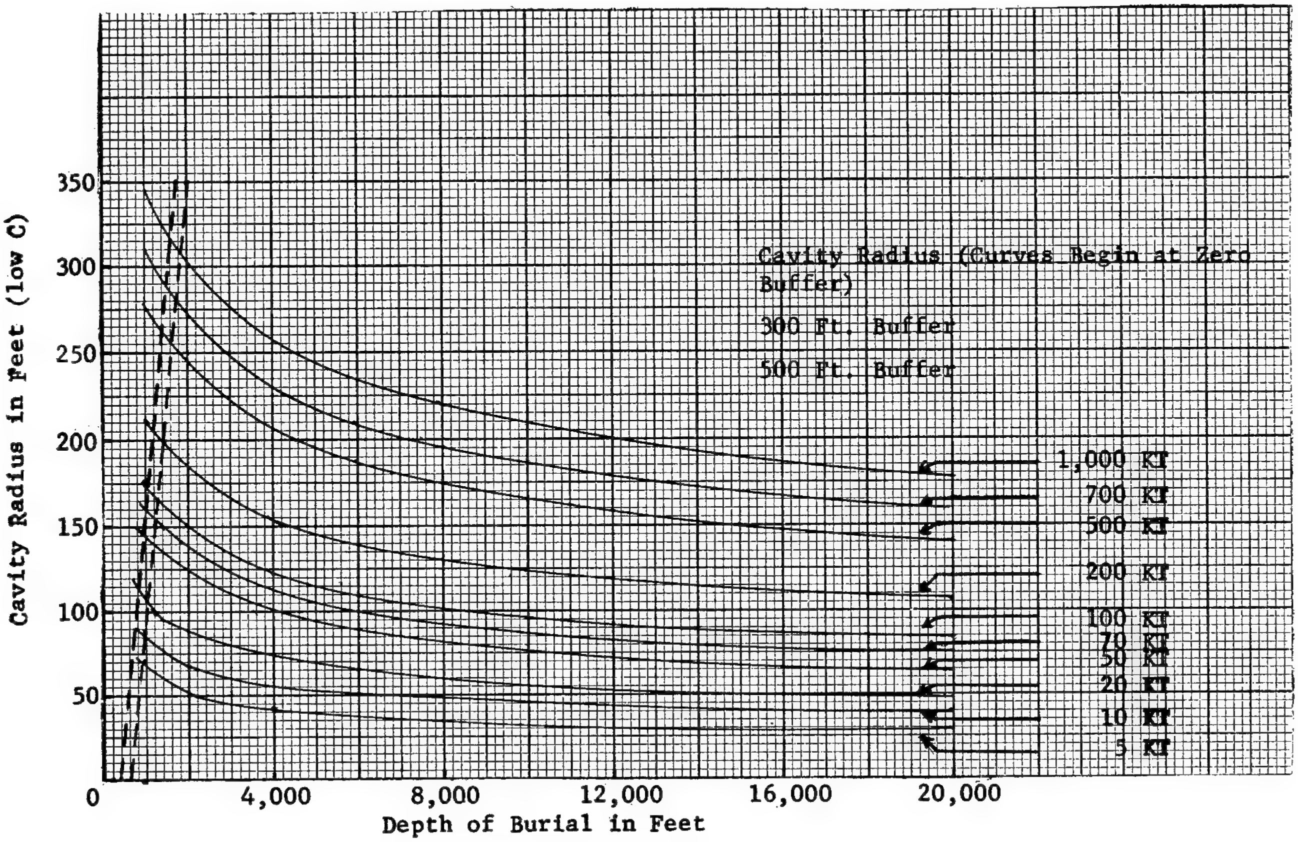
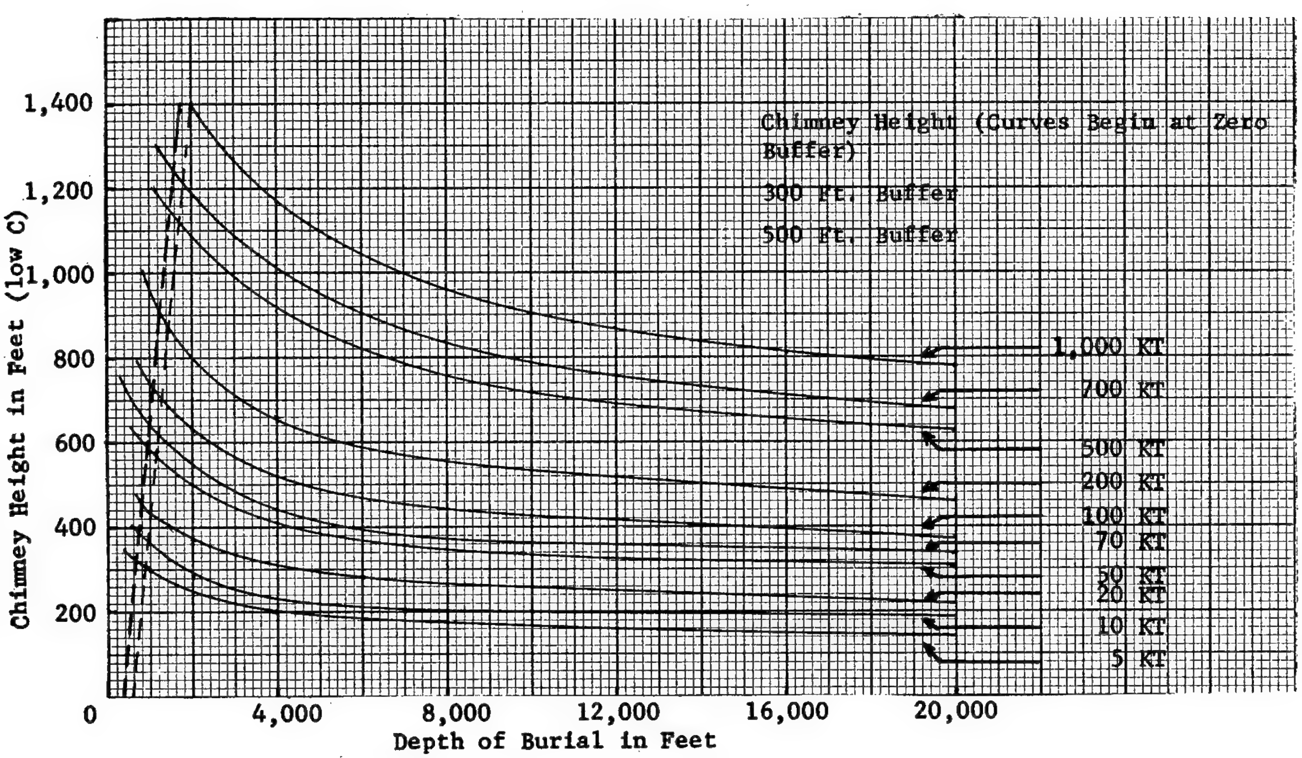


Figure 1.2--Chimney Height for Underground Nuclear Explosions



where

H_f = Height of fractured zone

R_f = Radius of fractured zone

The factors C_f and C_r are still unknown to a large extent and all values used now are educated guesses ($C_f \approx 7$, $C_r \approx 4$). Also C_f and C_r hardly have the properties of constants and may be functions of the medium in which the device is exploded and the depth of burial. At large depths (10,000 - 12,000 feet and more), initially created fractures might close again. The empirical values for C_f and C_r are of decisive importance in the economics of gas stimulation by nuclear explosives. This is especially true for C_f, since the fractures around the cavity increase the permeability of the gas bearing formation and the value of C_f determines directly the volume of gas tapped by nuclear explosions. Figure 1.3 shows the environment resulting from an underground nuclear explosion and some of the concepts involved in natural gas stimulation [252].

Once these parameters are established by means of experiments, the volume of the rubble chimney and the fractured zone can easily be calculated by equations (5) and (6). In case the cavity does not collapse we have:

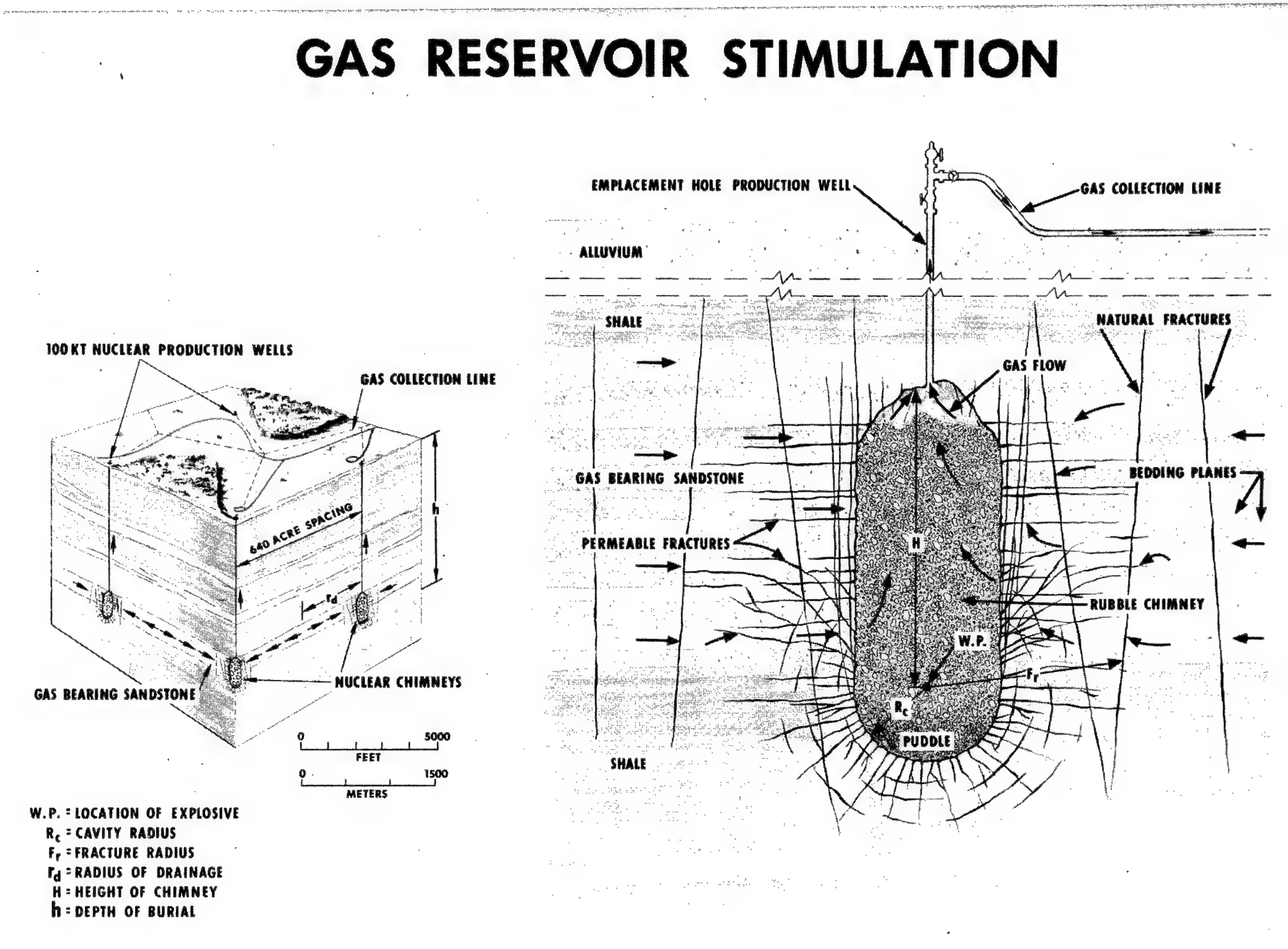
$$V_s = \frac{4}{3} \pi R^3 \qquad (5)$$

and in case of collapse:

$$V_c = \pi R^2 H - \frac{4}{3} \pi R^3 \qquad (6)$$

The volume of the fractured zone could again be approximated by the cylinder described by H_f and R_f [16, p. 49].

Figure 1.3



SOURCE: UCRL-Livermore, Graphic Arts, Neg. No. GLC-665-3757, PNE-616.

The information derived from experiments is needed to make more definite appraisals of the cavity volume and the volume of the fractured zone [33].

The distinction between the cavity volume and the extent of fractured zone is, in the case of gas stimulation, of very great importance. In order to understand better the relevance of the fractured zone one has to come back to the reasons why and how the conventional gas wells deliver gas.

Originally gas was nearly exclusively produced together with oil in the form of "associated" gas. Even today in the Near East substantial amounts of gas that occur as a by-product of crude oil production are simply flared (burned). It is on the basis of this "associated" gas that many of the subsequent reserve figures were arrived at by earlier authors. "Non-associated" gas, however, does occur in substantial amounts in sedimentary rock formations. Gas also occurs, as we will see later, in the so-called "black shales" of the Alleghenies. The vast reserves of "non-associated" gas seem, in part, to be associated geographically with oil shale formations in the U.S. Within the gas-bearing rock formation there exists a certain pressure which is exerted by the gas "stored" in the rock. The potential "storage" capacity of the rock itself is determined by its porosity. From this one has to distinguish the flow of gas within the rock formation which is determined by the permeability of the formation, i.e., the ability of the gas to flow within the rock formation. If, now, at any point in this formation a well is drilled and some amount of gas is withdrawn from the gas bed (very often at high pressures), a pressure differential is created. The pressure in the cavity of the well decreases and, if the permeability of the surrounding rock is great enough, the cavity will be filled up by high pressure gas which flows now from the surrounding area to the low pressure cone around the well bore. The

further the continuous fracture system extends from the wellhead into the surrounding medium, the more gas will be drained from the surrounding area. Normally gas flows through inter-granular pore space. If the natural permeability of the formation is, however, insufficient, then the gas flow can be induced by fractures. Gas pressure, ability of the gas to flow (permeability) and total amount of gas per well unit will ultimately determine the productivity of the gas well. However, actual well spacing is dependent upon depth, state regulations and economics, among other considerations, and thus the 160 acre estimate is rather a broad generalization. In nuclear stimulation a similar production unit could be chosen, but, depending on the extent of the fractured system, a larger unit, i.e., 320 or 640 acres per wellhead, may be desirable depending on the yield of the nuclear device, the chimney volume, and especially the extent of the fractures around the chimney (the value of C_f).

The extent of fracturing will not only be a function of the depth at which the device is emplaced and its yield but also of the lithology. Estimates, obtained so far only for media not containing hydrocarbons gave the following results [1, p. 27 and 34, p. 124]:

Table 1.3--Maximum reach of fractures above shot point.

	Yield (KT)	R (ft)	Medium	R_f (ft)	C_r
Gnome	3.1 ± .5	57	Rock Salt	350	6.1
Hardhat	5.0 ± 1.	63	Granodiorite	483	7.7
Rainer	1.7	65	Tuff	386	5.9
Blanca*	19.2 ± 1.5	145	Tuff	988	6.8

*Formed a subsidence crater.

SOURCE: Piper, A.M., Stead, F.W., "Potential Applications of Nuclear Explosives in Development and Management of Water Resources - Principles," USDI, TE1-857, March 1965.

Boardman, Charles R., Rabb, David D., McArthur Richard D., "Characteristics Effects of Contained Nuclear Explosions for Evaluation of Mining Applications," LRL, Livermore, California, UCRL-7350 Rev. 1, September 1963.

The extent of the fractures shown in Table 1.3 was determined from exploration holes drilled around the explosion area. The loss of circulation of drill fluid in wells drilled around the explosion area suggests that the extent of very small fractures could well have exceeded by a considerable amount the observed fracture system. In gas stimulation even hairline fractures suffice to establish a gas flow to low pressure areas. The presence of hydrogen (water) may further enhance the extent of the fractures.

Arguments against a substantial further increase of fractures beyond these observed values were given by A. Holzer and D. E. Rawson [10, p. 50 f.]. They pointed out that permeability increases associated with explosions in volcanic tuff and alluvium are generally much less, due to the compactness and plasticity of the materials. This argument could, to some extent, apply also to sandstones and shales, though no tests were conducted in these media.

Temperature increases around the center of explosion are described in the General Report on Plowshare by MATHEMATICA, and would not differ from explosions in other media. After a well is drilled into the gas formation and the well itself has been stimulated either by conventional means (hydraulic fracturing) or by nuclear explosives, we have again to distinguish between the immediate gas flow residing

from the well and the long run stablized production flow of the gas well. Over time the gas flow from the well will decay more and more. Conventional gas wells have usually a life span of about 20 years. Nuclear stimulated wells may exceed this figure and develop a production history up to 30, if not 50 years. The reasons for this are first, the large chimney volume and second, the large extent of explosively created fractures [5, 10, 15, 16, 51]. However, the main object of gas well stimulation is the increased production rate, not the potential extension of the life of gas wells; this is due mainly to the negligible benefits of revenues discounted for 30 or 50 years.

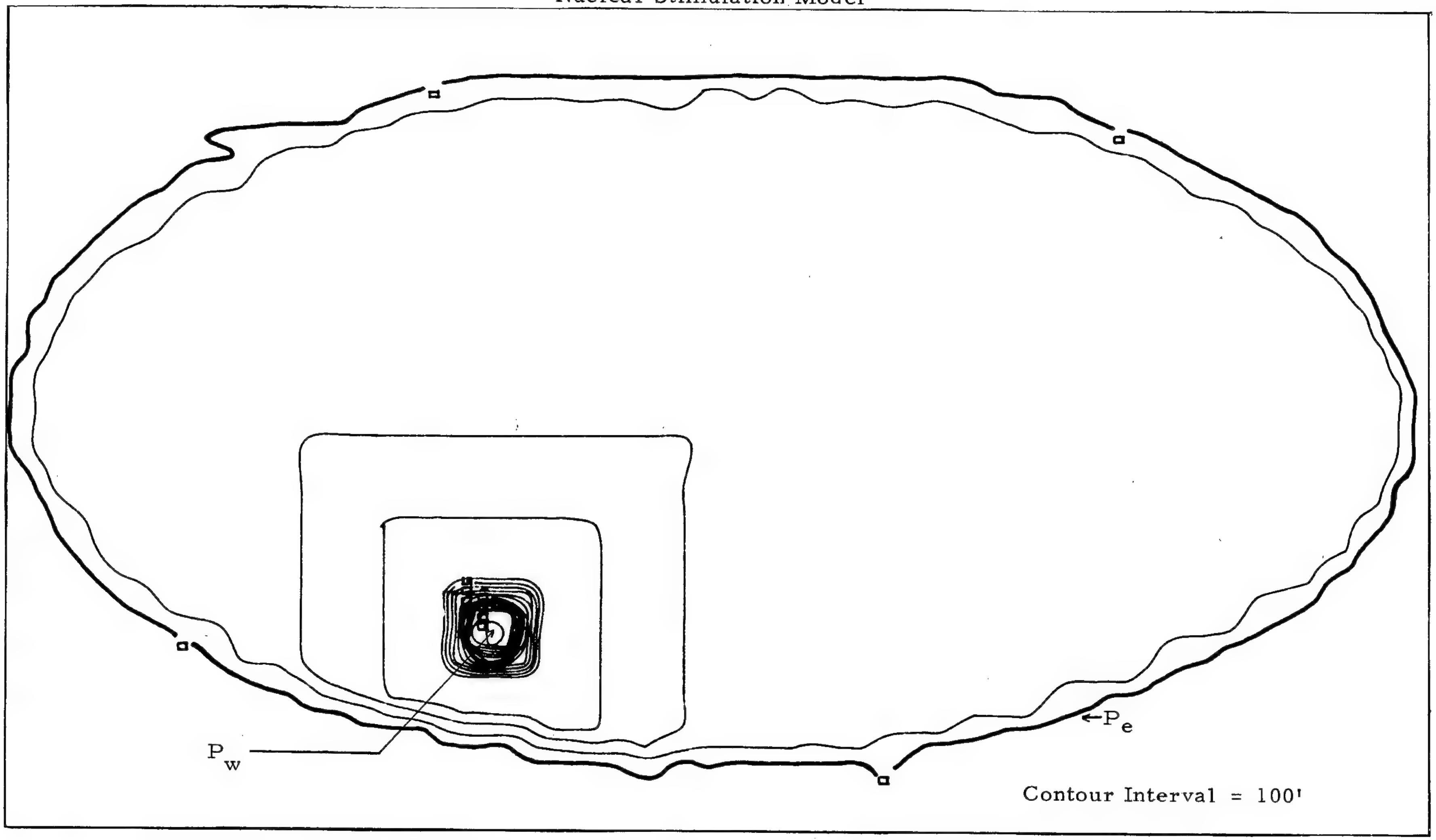
Today in gas well production,various forms of prediction models are used of which (1) the radial, steady state model, (2) the radial, unsteady state, symmetric model, and (3) a more recent, three-dimensional, unsteady state, non-symmetric model are most widely used in the gas industry [10, 15, 16].* The most simple of these three models states that the rate of flow in cubic feet per day (CFD) at a certain pressure base is proportional to the permeability of the reservoir rock, the net thickness of the gas-bearing formation, the squared difference in the static reservoir pressure and the squared flow pressure at the wellbore. Production is inversely proportional to the viscosity of the gas, the natural log of the ratio of the effective radius of drainage to the radius of the wellbore, the temperature of the reservoir and the gas compressibility factor. Equation (7) states this rather simple model [10, p. 43].

$$Q = \frac{10.320\ kh(Pe^2 - Pw^2)}{\mu \ln(Re/Rw)T_f\ 15.025z} \tag{7}$$

---

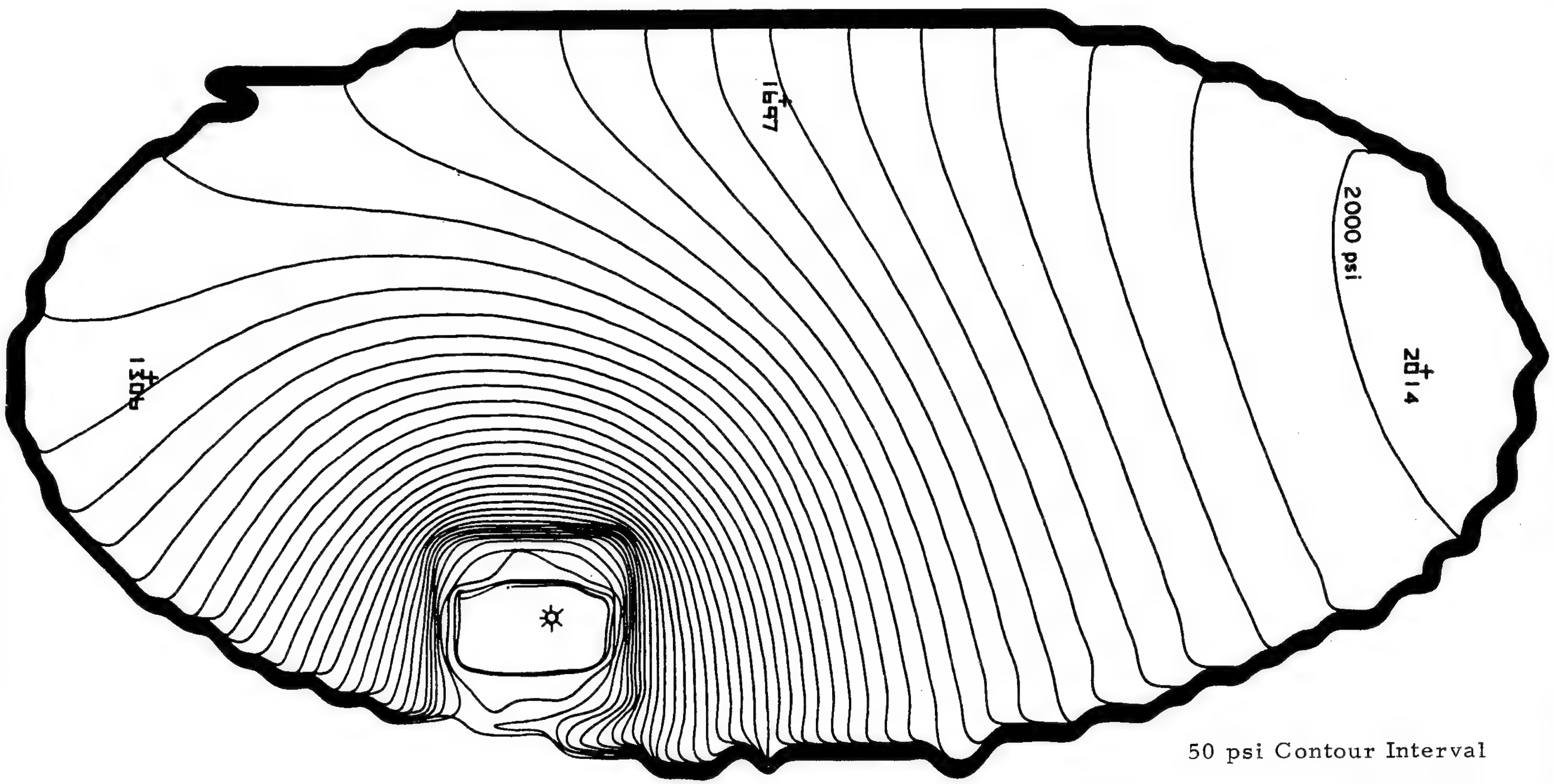
* Figures 1.4 and 1.5 show the simulated gas flow of such a three-dimension prediction model immediately after the shot (Figure 1.4) and 20 years after nuclear stimulation (Figure 1.5).

Figure 1.4--Isopach Map
Mesaverde Reservoir
Nuclear Stimulation Model



SOURCE: C. E. R. Geonuclear Corporation, Austral Oil Company, "Project Rulison Feasibility Study," 1966.

Figure 1.5--Isobaric Map
After 20 Years of Production
Nuclear Stimulated Well
Case C in Figure 3.5



SOURCE: C. E. R. Geonuclear Corporation, Austral Oil Company, "Project Rulison Feasibility Study," 1966.

where

Q = rate of flow CFD at the pressure base of 15.025 psia and $60^{o}F$

k = permeability in millidarcys

h = net sand thickness in feet

Pe = formation pressure at radius Re, psia

Pw = flow pressure at wellbore, psia

μ = viscosity, centipose

Re = radius of drainage, feet

Rw = radius of wellbore, feet

T_f = formation temperature, degree RANKINE

z = gas deviation factor.

From equation (7) it is evident that nuclear explosions would affect various parameters in this relationship and make Plowshare techniques potentially very attractive for the stimulation of gas fields, especially those which otherwise would not produce economically ("dry" wells - 250 MCFD* or less deliverability in tight formations):

a) In the case of gas flows, nuclear explosives increase considerably the permeability of the formation surrounding the explosion center (fracture chimney system).

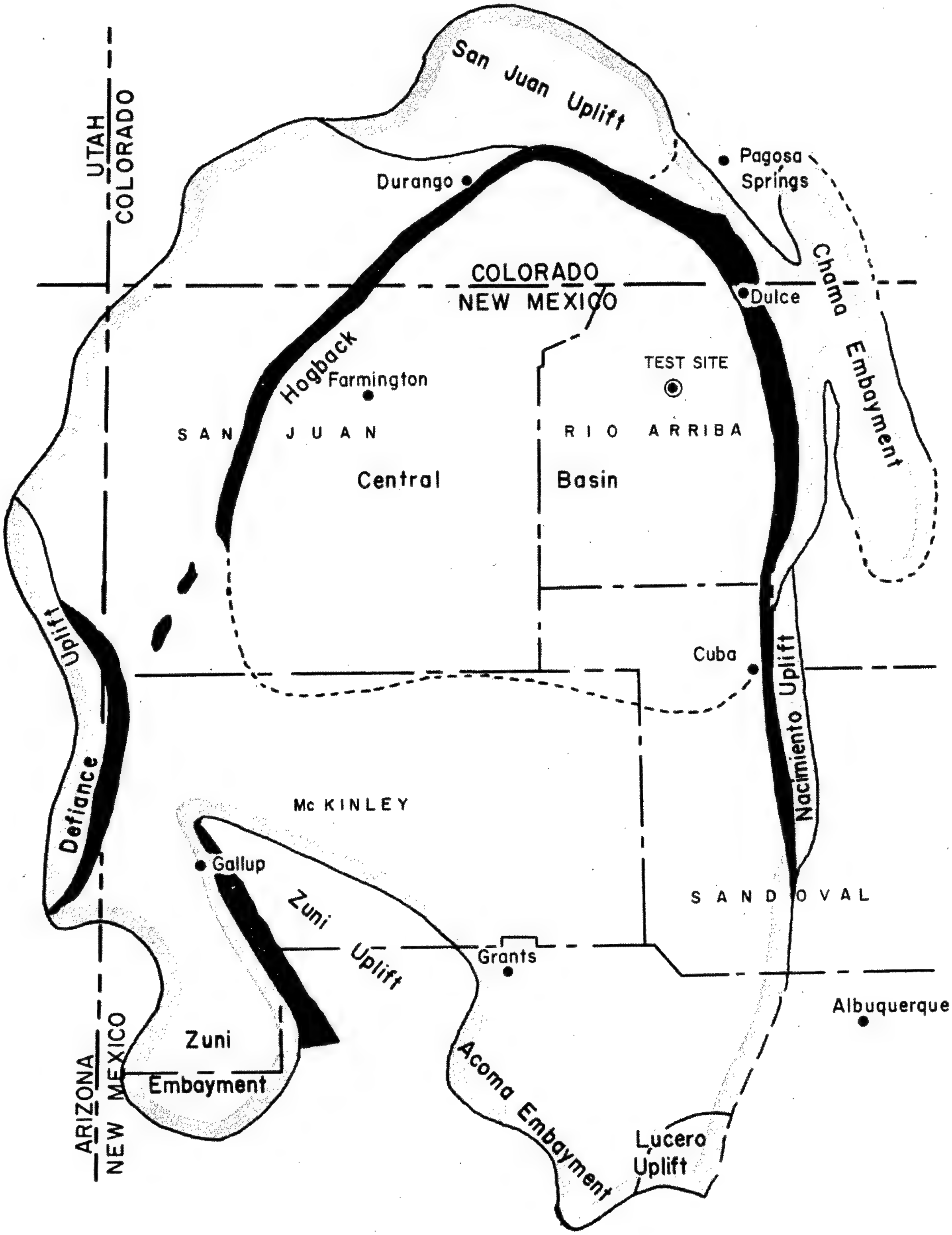
b) The radius of the well bore is considerably increased by nuclear stimulation (chimney formation fracture system). This means that the denominator in equation (7) decreases, i.e., overall gas flow in the well increases, though the increase might be relatively small due to the log-dependence.

* MCFD = Thousand cubic feet per day; not all gas bearing formations of 250 MCFD or less are, however, suitable for nuclear stimulation.

c) It is important in gas stimulation that, per explosion, gas-bearing formations should be "connected" in the vertical extent of the field as much as possible, i.e., the pressure differential created by the drainage of gas at the well bore should extend effectively throughout the overlying gas-bearing rock formations. This suggests that a multiple vertical emplacement of nuclear explosives would achieve optimal results in many of the fields (in the Green River Basin where the thickness of potential gas-bearing sandstone is 2,500 feet and more) which simultaneously would also ease seismic limitation imposed on explosive yields. At identical yields, a multiple vertical emplacement would achieve a more extensive connection of overlapping gas-bearing rock formations at the expense of reduced horizontal effect (chimney height vs. chimney radius and associated fractures). The seismic effects in such shots of identical overall yield would be reduced by an appropriate timing of the multiple explosions to successive events. Such a shot is at present contemplated in at least one proposal [15, 17] recently submitted to the AEC.

The present projections, however, are all extrapolations from earlier underground experiments in which the media did not contain any considerable amounts of hydrocarbons. Therefore, valid production predictions and a more detailed analysis of the potential of nuclear stimulation in gas fields can only be made after an effective experiment has been conducted. Figure 1.6 shows the location of the first proposed experimental project in gas. Some detailed case studies of various Plowshare applications already show the potential of gas stimulation if

Figure 1.6--Structural Elements of the San Juan Basin and Location of Gasbuggy Test Site



SOURCE: "Project Gasbuggy," Feasibility Study by the El Pase Natural Gas Company, U. S. Atomic Energy Commission, U. S. Bureau of Mines, Lawrence Radiation Laboratories, May 1965.

the parameters involved in nuclear explosions are somewhat similar [4, 10, 15, 16, 17]. In order to make statements on the minimum net thickness of the gas-bearing formation, the minimum pressure required in the gas field to get adequate gas flow after nuclear stimulation, the optimal spacing of nuclearly stimulated wells, maximum depth of emplacement, etc., more has to be known about the actual effects of nuclear stimulation. Such information will be available only after experiments have been conducted in the relevant media (chimney size, extent of fracture system, amount of radiological hazards).

Chapter 2

THE MACRO-ECONOMIC POTENTIAL OF NUCLEAR GAS STIMULATION

The potential in gas stimulation has to be evaluated and weighed against the generally available knowledge on fossil fuel energy resources in the United States and the world, and the particular prospects of gas stimulation by nuclear explosions within the overall fossil fuel balance. The evaluation of the U.S. fossil fuel reserves by present techniques is shown in Table 2.1 which was compiled by the Department of the Interior [derived from 24, p. 6].

Table 2.1--U.S. Resources of Fossil Fuels
(Energy Equivalents in Q = 10^{18} Btu)

	Known Recoverable Resources	Undiscovered Recoverable Resources*	Known Marginal Resources	Undiscovered Marginal Resources*
Coal	4.6	n-e	29.	55.
Petroleum	.28	1.15	.2	1.7
Nat. Gas	.3	1.3	n-e	.9
Nat. Gas Liquids	.03	.14	n-e	.3
Oil in Bituminous Rock	.01	n-e	n-e	.1
Shale Oil	.5	n-e	11.6	23.2
Total Q	5.7	2.6	41.	81.*

U.S. Consumption in 1960 0.06 Q
n-e = not estimated

SOURCE: U.S. Department of the Interior, "The Oil Shale Problem," A synopsis prepared for the opening meeting of the Department of the Interior, Oil Shale Advisory Board, July 1964.

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* Estimates of this kind occur frequently in the literature. The term "undiscovered resources" is used in various Department of the Interior publications. These columns refer to resources which are expected to exist but the exact extent of which has not yet been determined.

A similar breakdown of world reserves is shown in Table 2. 2 with all the faults such a table necessarily has [derived from 24, p. 10].

Table 2. 2--World Resources* of Fossil Fuels (Energy Equivalents in Q = 10^{18} Btu)

	Known Recoverable Reserves	Undiscovered Marginal Reserves**
Coal	18.	320.
Petroleum	1.7	23.
Nat. Gas	2.0	21.
Nat. Gas Liquids	.2	3.2
Oil in Bituminous Rock	.2	6.1
Shale Oil	.9	79.
Total Q	23.	452.**

World consumption in 1965 = 0.3 approximately

*The reference states "world reserves." As the table does include, however, "undiscovered, marginal reserves" the term resource is used here.

**See footnote on previous page.

SOURCE: U.S. Department of the Interior, "The Oil Shale Problem," A synopsis prepared for the opening meeting of the Department of the Interior, Oil Shale Advisory Board, July 1964.

Both tables give some insight into the overall United States and world energy situation if the present structure of energy supply is somehow maintained, i.e., over 90 percent of total energy demand is supplied by fossil fuels.

Both within the United States and worldwide, natural gas reserves and resources are insignificant if related to the energy equivalents contained in known and expected coal and oil shale deposits. Nevertheless, gas is today an important energy base within the United States. This, in part, is due to the known, favorable properties of this product when compared to

other fossil fuels. Thus any extension of recoverable natural gas reserves by technological breakthroughs must be considered as very desirable, as long as the costs associated with this technique can be covered by the price of the product. During the last decades, U.S. production and estimated U.S. proved reserves of natural gas followed a path similar to the one to be found in the oil industry: production expanded considerably, proved reserves were expanded too, but the relation between the two figures is narrowing more and more as is evidenced by Table 2.3 [20, p. 406]. Figure 2.1 gives a graphical representation of Table 2.3.

Table 2.3--U.S. Natural Gas Production and Proved Reserves in TCF**

Year	Withdrawals during year	Estimated Proved Reserves end of Year*	Reserves as Multiple of Current Production
1945	4.8	147.8	30.8
1950	7.1	185.6	26.1
1955	10.2	223.7	21.9
1960	13.3	263.8	19.8
1964	17.0	281.3	16.6

* Report of the Committee on Natural Gas Reserves of the American Gas Association for year ending December 31, 1961.

** TCF = trillion cubic feet

SOURCE: Landsberg, H.H., L. L. Fischman, J. L. Fisher, Resources in America's Future - Patterns of Requirements and Availabilities, The Johns Hopkins Press, 1962.

As in the case of the American Petroleum Institute's estimate of crude oil reserves, the above table gives a very conservative estimate of recoverable gas reserves. Other estimates were advanced and are given here.

Figure 2.1--U.S. Gas Production and Reserves as Multiple of Production

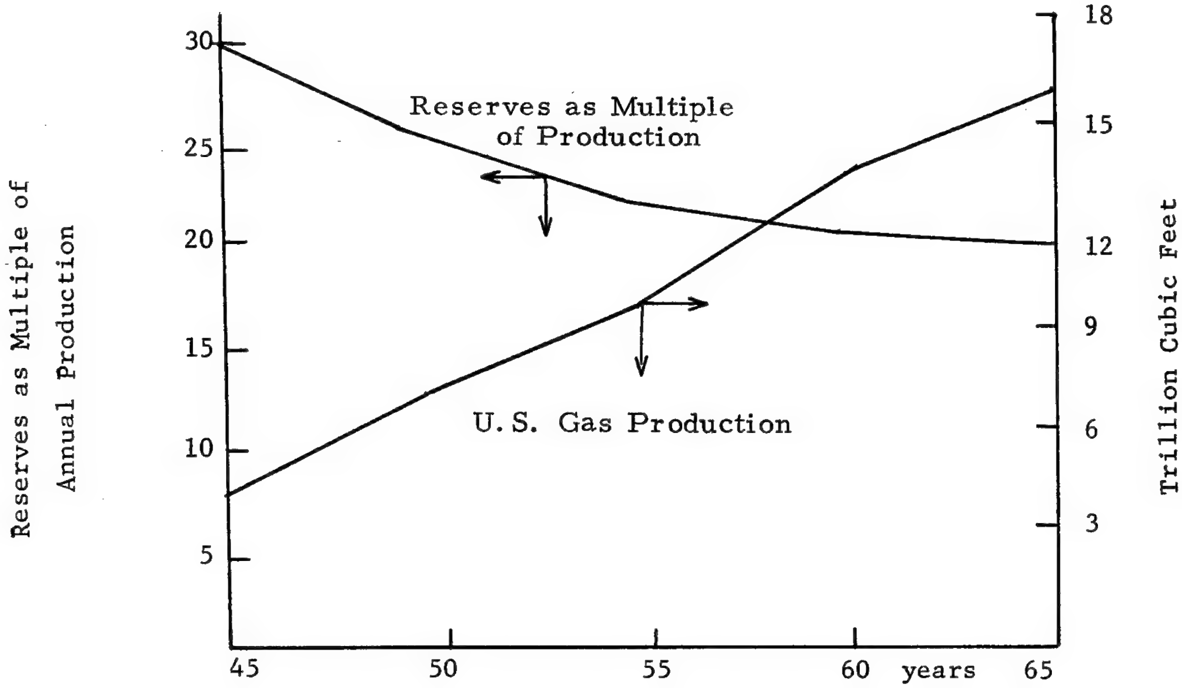
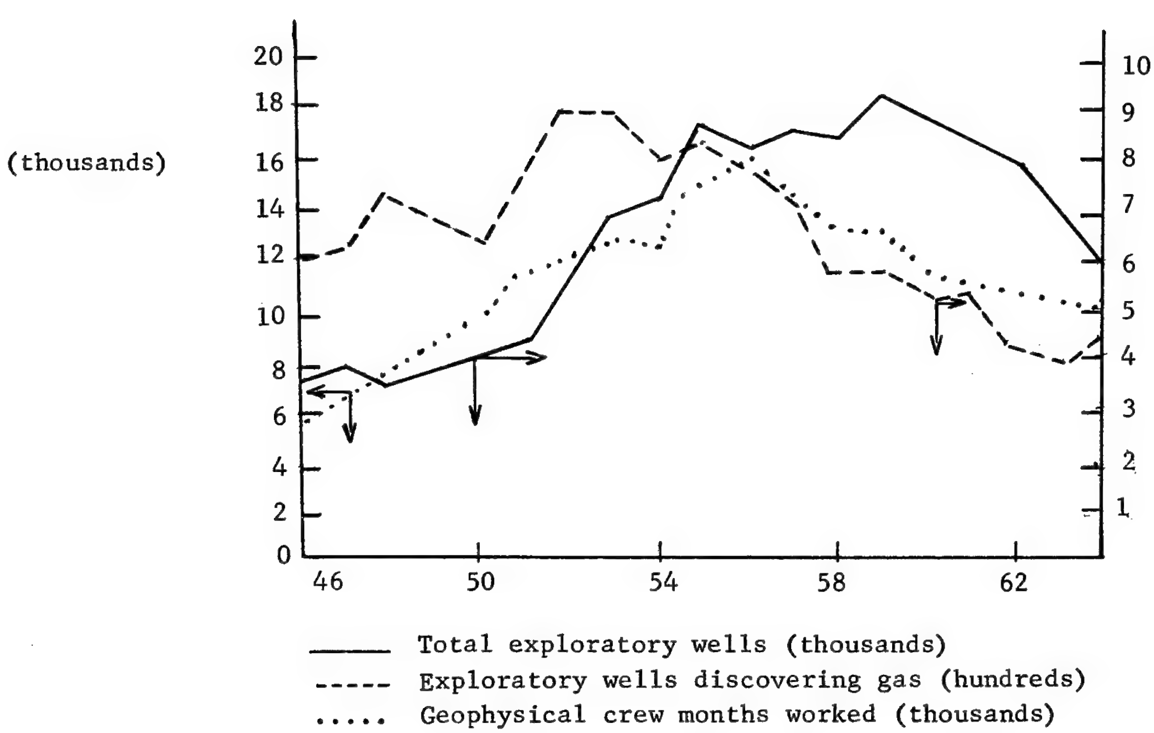


Figure 2.2--U.S. Exploratory Activity and Gas Discoveries



B. C. Netschert (1958) [25] gave the total amount of gas recoverable in the future as ranging between 510-1, 200 TCF.

M. K. Hubbert (1962) [26] gave an estimate of the total ultimate supply of natural gas in the United States of 1, 000 TCF, but admitted that this reserve figure could range from anywhere between 600 to 2, 650 TCF.

L. G. Weeks (1959) [27] gave potential untapped reserves of 1, 000 TCF to which cumulative production of 161 TCF had to be added to make it comparable to the other estimates advanced previously.

The U.S. Department of Interior Energy Policy Staff (1963) [9, 28] gave a further breakdown of these reserves:

Undiscovered reserves	1, 200 TCF
Discovered Reserves	268 TCF
Cumulative Production	161 TCF
Total of Recoverable Reserves	1, 629 TCF

To appreciate, however, the quality of such estimates, a more detailed discussion of the most recent estimate by T. A. Hendricks is instructive and will shed some further light on the previous estimates. It so happens that substantial amounts of oil and gas occur sometimes in one and the same formation. In other formations mainly oil or mainly gas are present. Gas which occurs together with oil is also called "associated" gas, and in the early production history of oil it was flared. Today the flaring of gas does still take place in some of the Arabian countries, and the energy contained in these wasted hydrocarbons is substantial (see above). However, nothing is known about the generation of both gas and oil which would enable one to adopt a "natural" ratio in which both substances were

formed historically. The data on gas reservoirs and their extent are so scant that at some point somebody must have suggested that the best way to estimate potential gas reserves was to regard their occurrence as a simple given multiple of known or assumed oil reserves. In order to measure this relationship nothing else was done but to take oil and gas production figures over the last decades, relate them and extend this relation to the estimate of total gas reserves ever to be discovered by multiplying the crude oil reserve estimated by this multiplier. T. A. Hendricks ends up with a 2,500 CF estimate of gas for each barrel of crude oil. This figure was derived by Hendricks from American Petroleum Institute and American Gas Association figures of 1952-1956 which showed 6,182 CF for each barrel of crude oil produced, and from the 1957-1962 figures which showed a 6,637 CF per barrel of oil crude produced. Though Hendricks noticed the rising trend toward gas production, he claims his estimate to be conservative by applying the 6,637 CF per barrel of crude oil figure. As the recovery rates of crude oil in place and gas in place differ (30 per cent for the former, 80 per cent in the case of gas production) the multiplier for "crude oil in place reserves" turns out to be 2500 CF per barrel of crude oil in place [11, p. 11]. This multiplier itself is then applied to the questionable oil reserve figure arrived at by T. A. Hendricks. Thus, T. A. Hendricks uses a "Bayesian" table shown below: [11, p. 12].

The only figure which is somehow founded on empirical evidence is the 400 billion barrel estimate for recoverable crude oil reserves (except the figures in the last line). From that figure the 1,600 billion barrel figure was arrived at and the whole set of gas reserve figures was obtained by using the 2,500 CF per-barrel-of-crude-oil multiplier.

Table 2.4--Oil, Gas, and Natural-gas liquids in place in the United States before production began

	Crude Oil Billion Barrels	Natural Gas TCF	Natural Gas Liquids Billion Barrels
Total in Place	1,600	4,000	120
Total in place to be found by exploration	1,000	2,500	75
Economically Recoverable	400	2,000	60
Submarginal	1,200	2,000	60
Approximate Production through 1961	68	230	7

SOURCE: Hendricks, T.A., "Resources of Oil, Gas and Natural Gas Liquids in the United States and the World," U.S. Department of the Interior, GSC 522, 1965.

This is not to say that any of the other figures mentioned on total gas reserves in place are any better: they are all based on similar principles of "estimation", except of course, the American Gas Association's measured reserves which, however, do not pretend to be total reserves of in-place recoverable gas.

It is possible to obtain better estimates of total gas reserves expected to be in-place. The Petroleum Information Corporation in Denver, Colorado, disposes of a vast amount of well-analysis data of productive and unproductive, exploratory and commercial wells. One would then have to make a basin-to-basin estimate from the few data which are available, and obtain at least a minimum overall total reserve figure. For conventional production methods in gas fields, T.A. Hendricks' estimate of gas "economically recoverable" might be a very high estimate given that it is "based" on crude oil recoverable reserves of 400 billion barrels. Once, however, nuclear techniques are developed which would stimulate low permeability gas fields, fields which per well would yield less than 250 MCFD with conventional techniques, the total gas recoverable will add significantly

to present estimated recoverable reserves: T. A. Hendricks' estimate can well be classified as reflecting "associated" gas estimates, given his estimating procedure. Known quantities of non-associated gas, however, exist in at least two areas extending over thousands of square miles in the United States, often in geographical association with oil shales. These reserves occur mainly alongside and south of the Rocky Mountain oil shale basins (in very sparsely populated areas) and in the "black shales" along the Alleghenies, where the thick formations again occur in relatively sparsely populated areas. The gas reserves are located in such a way that

a) Plowshare techniques could readily be applied

b) The main centers of demand (East Coast, West Coast, area around the Great Lakes) are relatively close to one of the areas.

c) Resources in both areas are very large by present production rates, though in the future gas demand might expand considerably.

For both the Rocky Mountain and Appalachian areas, reliable estimates as to their overall potential are missing. With regard to the Rocky Mountain area we know the approximate extent of the gas-bearing basins [10, p. 23] (See Table 2.5 and Figure 2.2) [253].

Table 2.5--Extent of Rocky Mountain Potential Gas-bearing Formations

Basin	Area with Production Potential (sq. miles)	Number of gas-bearing formations	Thickness of Potential gas-bearing sand-stones (feet)
Uinta	8,900	4	1,700
Piceance	3,900	4	1,200
Green River	19,000	7	2,500

(Table 2.5 - Continued)

San Juan	10, 600	8	10, 000
Paradox	25, 000	n. e.*	n. e.
Windriver	4, 000	n. e.	n. e.

* n. e. = not estimated

SOURCE: "Project Gasbuggy," Feasibility Study by the El Paso Natural Gas Company, U. S. Atomic Energy Commission, U.S. Bureau of Mines, Lawrence Radiation Laboratories, May, 1965, pp 8 and 23.

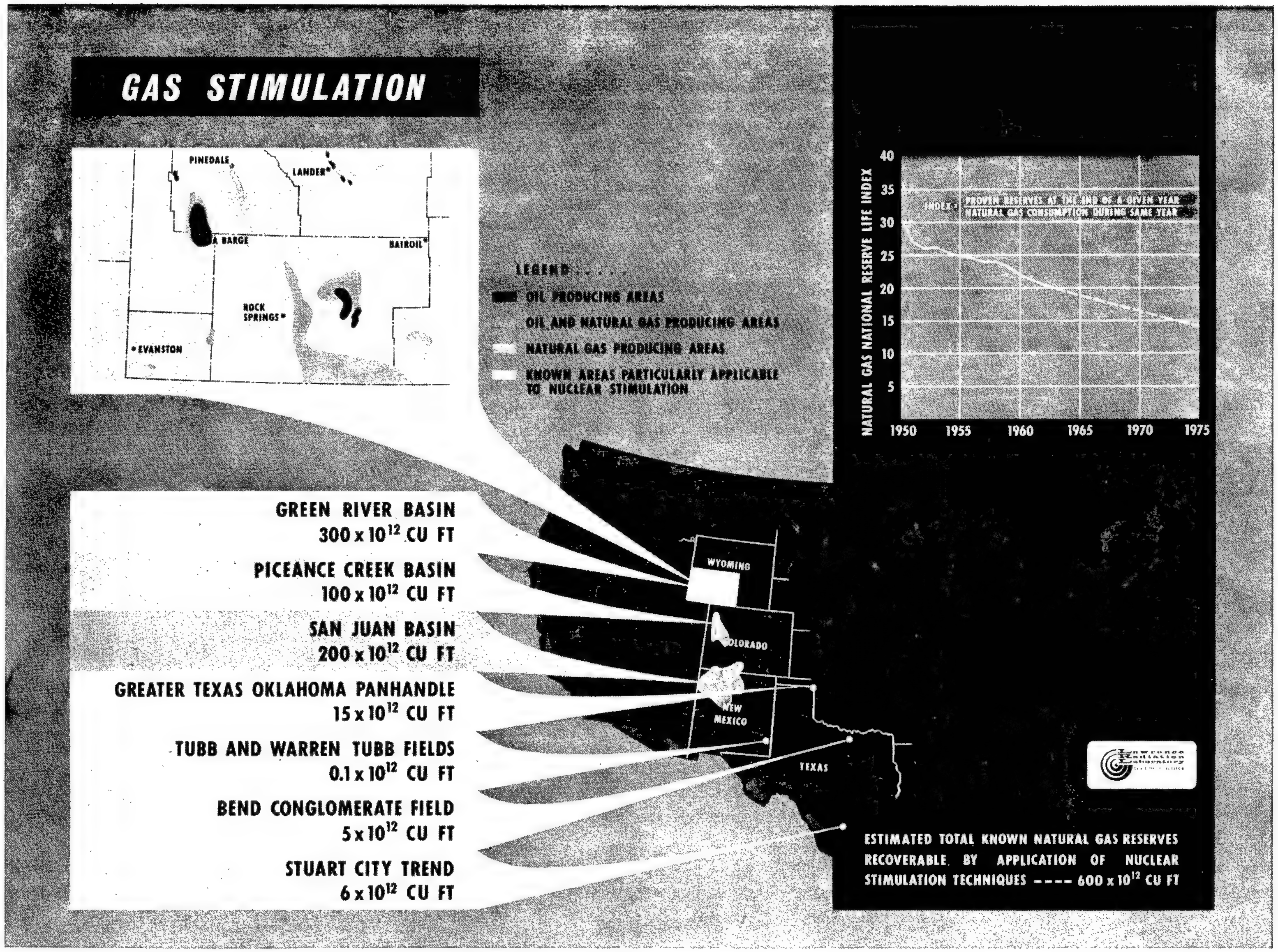
Estimates of total gas in-place reserves, if derived from a basin-by-basin evaluation are very likely to seem extremely large when compared with existing estimates of gas in-place reserves.

The figure cited most often in connection with gas stimulation by Plowshare techniques (in the Rocky Mountain area) is ≈ 320 TCF [7, 60]. This amount is equal to the American Gas Association's total figure on known, recoverable reserves (see above). This 320 TCF estimate seems, however, to be very conservative. Other estimates were advanced, one in the neighborhood of 600 TCF for three of the major basins alone [52, 253] and those in Figure 2.2This figure itself, if taken as an estimate for the whole Rocky Mountain area, is again on the more conservative side, as it does not include other major basins in that area.

Since such tight formations could not be brought into production economically up to now, such reserves were not included in many of the previous estimates in the first place, and well data are scarce for the same reason.

Given the area extent of the potential gas fields cited in Table 2.5 and all the well data available in that area, one could obtain a more

Figure 2.2



SOURCE: UCRL-Livermore, Graphic Arts, Neg. No. GLC-669-8254, PNE-798.

precise estimate of gas in-place reserves. As long as such an evaluation is not made, one is left only to speculation. Thus, at an average gas occurrence of 10 BCF per square mile (=1 section in nuclear stimulation) at total depth the Rocky Mountain Area should contain resources of about 700 TCF gas in-place, such that about 300 TCF might be recoverable by nuclear stimulation.

Furthermore, at an average 50-60 BCF per square mile of gas in-place at total depth (i.e. comprising all formations that occur at different depths)* the Rocky Mountain Area would yield an approximate gas in-place reserve of 3.5 to 4.2 QCF**. The 50-60 BCF estimate of gas in-place in <u>all</u> formations may be compared to some known, measured values of gas in-place in <u>single</u> formations: about 200 BCF per square mile in the Fort Union Formation in the Pinedale Unit Area (Green River Basin) [10], about 120 BCF per section in the Mesa Verde formation of the Piceance Basin, about 30 BCF in the pictured Cliffs Formation (Gasbuggy) [10], 10 BCF in the Mancos B formation in Blanca County (Piceance Basin) [16]. All of those formations can not be produced economically with present techniques because of their tightness or low reserve figures per section.

The 700 TCF estimate would more than double the present estimate of gas reserves in the U.S. The potential resources are, however, considerably higher and could be in the range just cited (about 4 QCF), though one has to treat such figures with very large qualifications. T. A.

---

* A 50 to 60 BCF per square mile would be a very high average quantity of in-place gas for entire basins and thus at least an upper bound to the potential resources present.

** QCF = Quadrillion CF (10^{15} CF).

Hendricks estimates a similar total of 4 QCF in-place resources for the U.S. [11, pp. 20ff].

The Devonian and Mississippian black shales might come close to the Rocky Mountain potential. Figure 2.3 shows the gas producing areas of the Appalachian region. At present, gas is produced there mostly from the sandstones overlying the black shales as some gas presumably escaped from the lower black shales and is now trapped in the higher formations. A substantial part of the gas (and shale oil) is, however, still contained in the tight, low-yield black shales [61]. The same is true for the fields in the Mississippian region.

For nuclear stimulation relatively thick formations are required, or a sequence of overlapping, thinner formations which can be connected by nuclear stimulation. Such gas-bearing formations also occur in the lower part of the Appalachian basin along the Kentucky-West Pennsylvania line [61], see Figure 2.3, and possibly also in the Mississippian region. The shale oil content of these regions and its potential recovery by Plowshare techniques are analyzed in the Special Report on Oil Shale by MATHEMATICA. The potential methane yield equivalent of the total organic reserves in these formations was estimated by E. B. Shultz as 8 QCF for better grade deposits and an additional 16 QCF for lower grade deposits, i. e., a total of 24 QCF in these basins [31].

Not all of these 24 QCF, however, are suitable for nuclear techniques. Much of the organic rich oil shale occurs in thin formations [30]. A substantial part of the gas (and shale oil) are present in the thick formations (i. e., exceeding 100-200 feet thickness). The exact potential of nuclear stimulation in these areas is again not known. But of the total 24 QCF estimate again 4 QCF might well be suitable for nuclear stimulation (subjective estimate). In energy equivalents the cited figures (700

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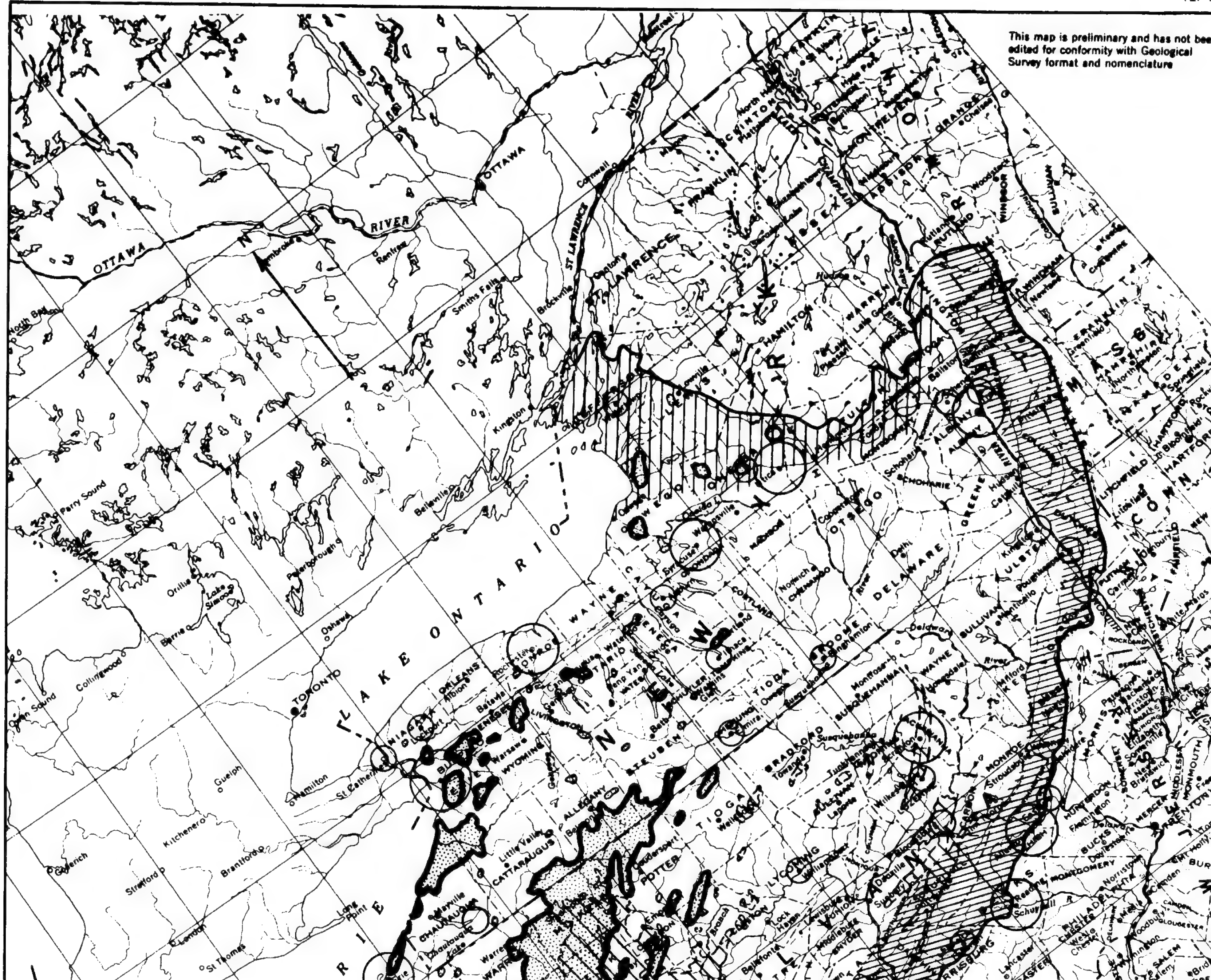


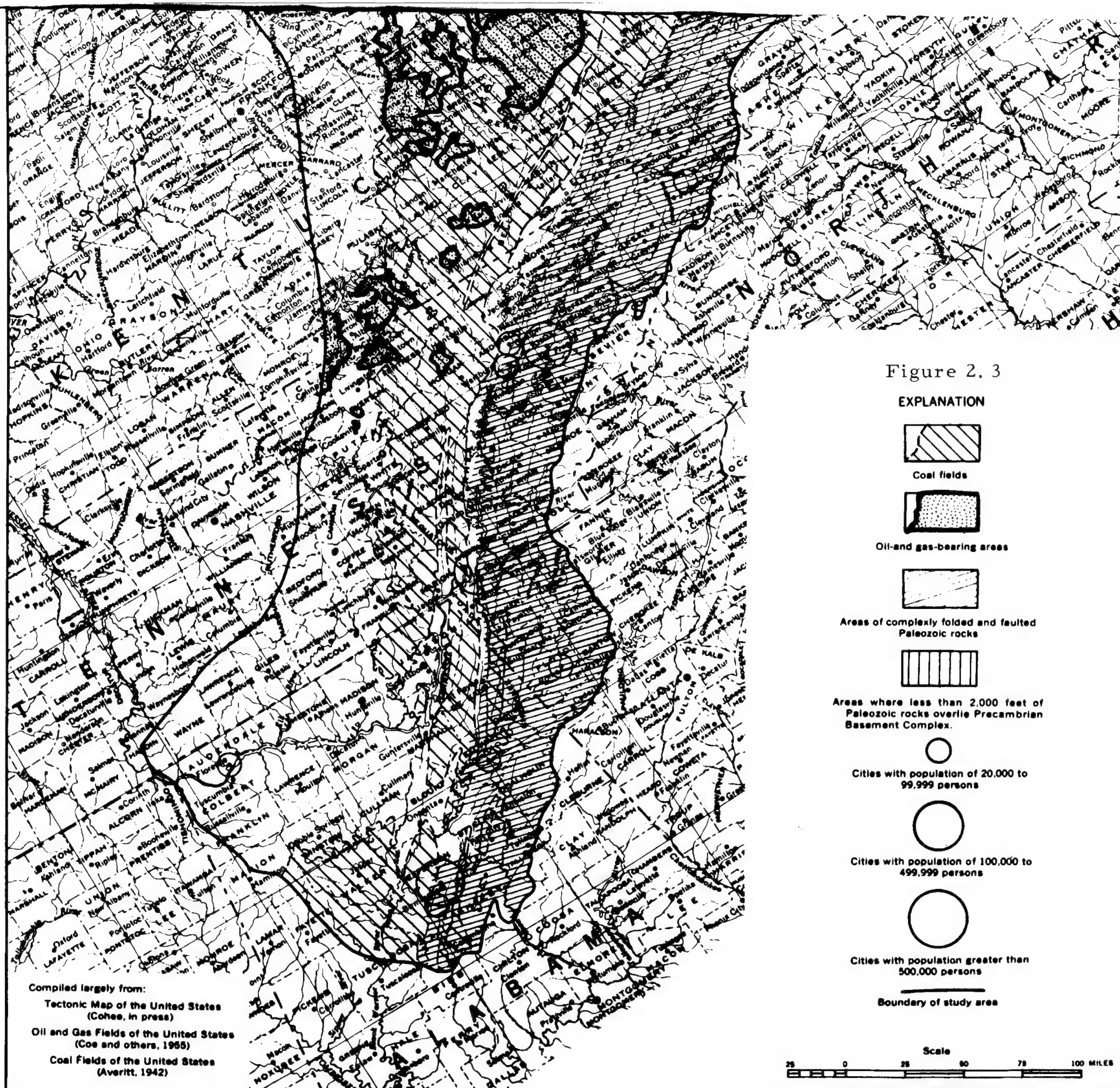


Figure 2. 3
EXPLANATION
Coal fields
Oil-and gas-bearing areas
Areas of complexly folded and faulted Paleozoic rocks
Areas where less than 2,000 feet of Paleozoic rocks overlie Precambrian Basement Complex.
Cities with population of 20,000 to 99,999 persons
Cities with population of 100,000 to 499,999 persons
Cities with population greater than 500,000 persons
Boundary of study area
Scale
25 0 25 50 75 100 MILES
Compiled largely from:
Tectonic Map of the United States (Cohee, in press)
Oil and Gas Fields of the United States (Coe and others, 1955)
Coal Fields of the United States (Averitt, 1942)
INTERIOR—GEOLOGICAL SURVEY WASHINGTON D C —1962

TCF, 4 QCF and potentially 8 QCF) correspond to 7 Q*, 4 Q and 8 Q respectively**, while present total annual U.S. energy consumption is about .06 Q, with gas accounting for about 0.015 Q. Of the above estimates, if about 50 per cent were recoverable by nuclear stimulation and if one allows for a 3 per cent long run expansion of gas demand (the present mid-1966 rate is 6 per cent [32]), then these supplies could cover demand for the next 18 years, 55 years and 75 years respectively. Present reserves recoverable by conventional techniques would last, at the same rate of expansion, for scarcely 15 years.

In addition to being used in these formations, gas stimulation by nuclear explosives might well develop to such a stage that even those fields which at present are developed only by conventional techniques (hydraulic fracturing) would be able to utilize, at least in part, the nuclear stimulation technique, local conditions permitting. This would then affect again the ultimate recoverable reserve figures (mainly the south-central region of the United States). No estimate of possible benefits in this area can be made now.

The nuclear stimulation technique would also allow for a more elastic production schedule. Due to the fact that the whole chimney volume has nearly infinite permeability, it can serve as a potential storage container for gas when irregular withdrawals of gas from the chimney occur. In conventional gas wells, production is only determined by the natural gas

---

* $1\ Q = 10^{18}$ British thermal units (Btu)

**Estimating 1 MCF as equivalent to 1 million Btu [59, p. 271].

flow induced by the pressure differential between the area immediately around the well and the surrounding gas-bearing formation. If withdrawal at the well is interrupted, the gas flow is interrupted and the induced gas flow starts more or less only after production has been resumed. Additional gas flow from the surrounding medium occurs mainly if gas is actually withdrawn from the well. During the initial phases of the well history, this would imply a postponement of revenue by about 20 years (the average life of a conventional well).

In the case of nuclear stimulation, the storage space within the nuclear chimney would still allow the gas to flow from the higher pressure in the surrounding formation to the relatively low pressure within the nuclear chimney. When production is resumed, the gas in the chimney can then be withdrawn at an increased rate. In May 1966 about 90 M^2CF of natural gas were stored underground [32]. Though gas storage itself should be as near as possible to the centers of demand (i.e., at the end of the gas transmission systems) the storage capacity of the nuclear chimney allows more elastic production schedules and in some cases directly allows for demand fluctuations.

Similar arguments hold for the stimulation of oil wells, though the extension of these reserves are less spectacular than those anticipated in oil shale and even in gas stimulation.

If the experiments show that the technical assumptions on gas stimulation are correct, the number of nuclear explosives demanded will be substantial. At a 100 KT average yield basis, the ultimate number of single applications would be above the 10,000 mark in gas stimulation

alone. Estimates of similar magnitude can be advanced also for other fields of completely contained explosives. Although these estimates are very tentative, they convey at least our idea of the order of magnitude some of the Plowshare applications may reach once this technology is developed and accepted.

Chapter 3

A MICRO-ECONOMIC EVALUATION OF GAS STIMULATION BY NUCLEAR EXPLOSIVES

As no nuclear explosive experiment has been made in media containing hydrocarbons in general and gas in particular, any statement made in this section is bound to be subject to considerable uncertainties. Unlike some other Plowshare projects, however, there are no additional uncertainties regarding the technology of recovery and processing. Once the uncertainties concerning nuclear explosions in hydrocarbons are cleared away, then, in the case of gas stimulation, no further technical problems exist.

The term "uncertainty" does not refer to possible large catastrophic events. Enough is known by now regarding the general effect of underground nuclear explosives to exclude any such event. The existing uncertainties are of a different kind and concern areas which will ultimately influence quite extensively the economics of gas stimulation (see Figure 3.1 derived from [5], [15] and [17]). There do exist, then, uncertainties as to:

a) The extent of fracturing in the surrounding rock (i.e., the induced permeability increase).

b) The extent of tritiation of the gas and possible decontamination techniques and costs. Substantial tritiation may be avoided, or restricted

so as to contaminate only about one chimney volume of gas.

c) The ultimate extent of reduction in the diameter of the nuclear device and the associated cost saving due to a reduced diameter of the emplacement well.

d) The ultimate AEC charge for the nuclear explosives in completely contained explosions. (See Figure 3.1 on present charges.)

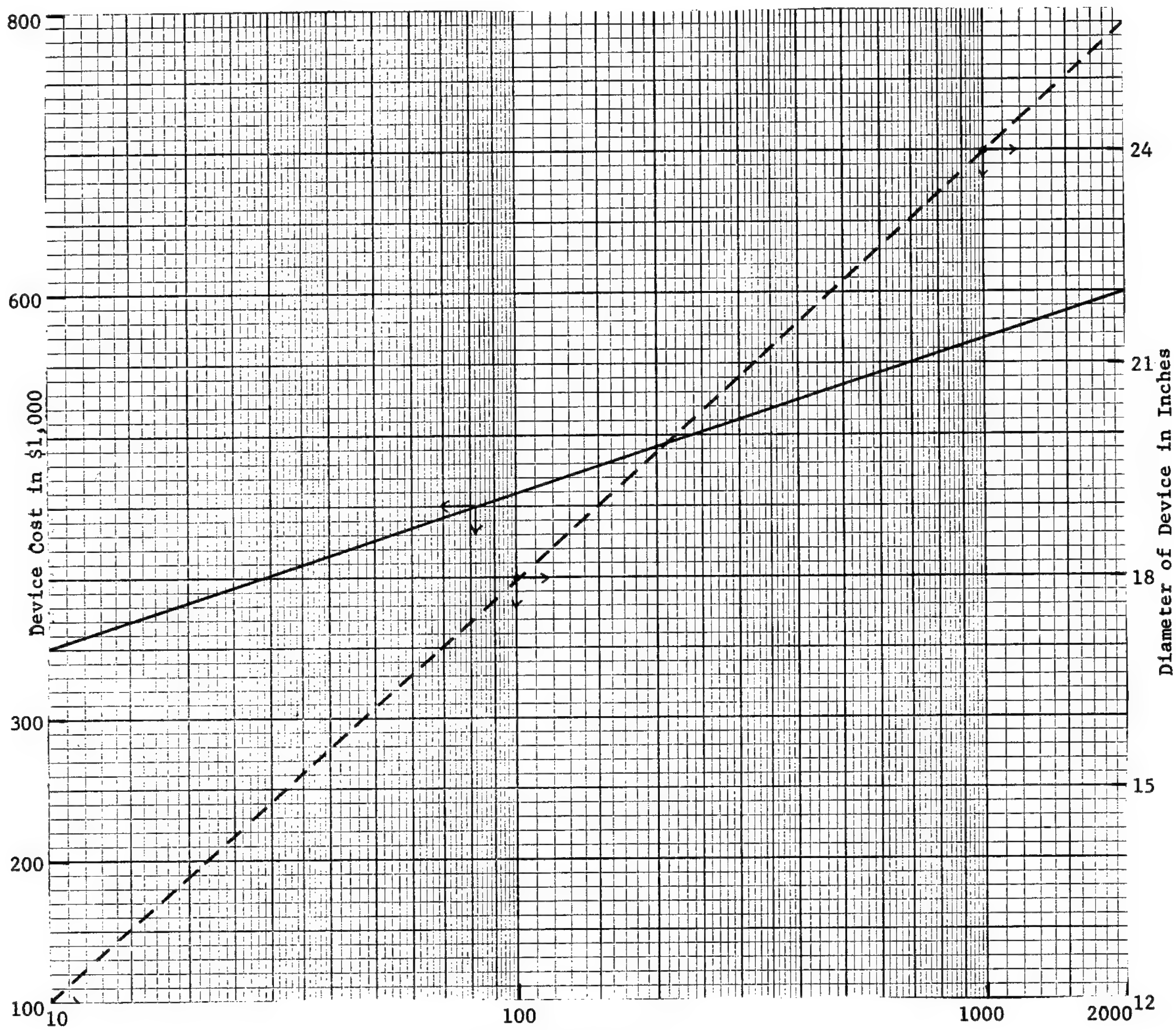
When most of these uncertainties are reduced or eliminated by experiments in gas formations, then this new technique can, potentially, be applied not only to tight, low permeability formations but possibly also to formations which at present are stimulated by conventional techniques (such as hydraulic fracturing). However, since experiments have not yet even been made, this possibility is quite remote.

The expected rate of return in nuclearly stimulated wells will mainly be a function of the gas in-place of the tight gas formation and the expected gas flow from this formation after the explosion took place. Figure 3.2 shows the expected increase of deliverable natural gas beyond conventional production for 34 BCF, 50 BCF and 100 BCF per section; the conventional well is assumed to produce from 100 BCF section.

Given the expected gas flows there remain still a variety of technical and economic parameters which will influence the effective rate of return of such wells.

In the following pages, four hypothetical cases are analyzed assuming in each of them (i) a low and (ii) a high increase in permeability by nuclear stimulation. The stimulated production capacities of the wells shown (in Case I expected production figures are entered) are evaluated at fifteen cents per MCF at well head. Operational costs are assumed to

Figure 3.1--Projected Charges and Diameters of Thermonuclear Explosives as a Function of Yield



10 KT ≧ 12 inches*
100 KT ≧ 18 inches*
1,000 KT ≧ 24 inches*
10,000 KT ≧ 36 inches (not shown)*

* Diameters of Nuclear Explosives

SOURCE: Information given by Atomic Energy Commission.

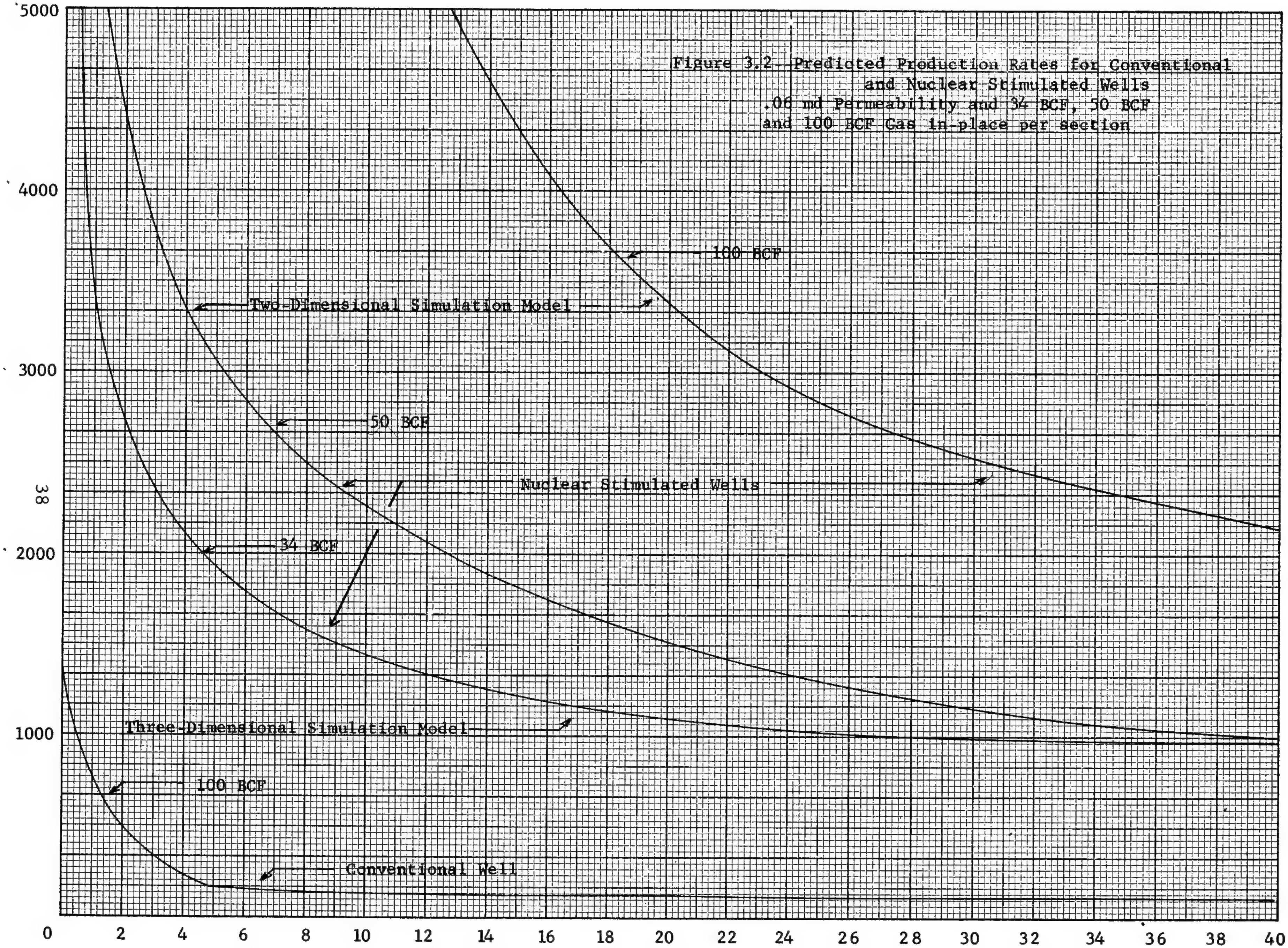


Figure 3.2 Predicted Production Rates for Conventional
and Nuclear Stimulated Wells
.06 md Permeability and 34 BCF, 50 BCF
and 100 BCF Gas in-place per section
100 BCF
Two-Dimensional Simulation Model
50 BCF
Nuclear Stimulated Wells
34 BCF
Three-Dimensional Simulation Model
100 BCF
Conventional Well
5000
4000
3000
2000
1000
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40

Table 3.1--Gas-Well Recovery by Nuclear Stimulation in low Permeability Fields in BCF**

	Recovery			
	Low*		High*	
PICUTRED CLIFFS (= Gasbuggy) (San Juan Basin)	BCF Recovered	Per cent Recovered	BCF Recovered	Per cent Recovered
(I) 10 Kt, 160 Acres ≈ 5 BCF gas in-place	3.5	67	3.7	71
10 Kt, 640 Acres ≈ 21 BCF gas in-place	6.1	29	7.8	37
30 Kt, 640 Acres ≈ 21 BCF gas in-place	6.8	32	8.7	41
[Conventional: 4 wells, each 160 acres, 5 BCF in-place]	-	-	[2.1]	[10]
MANCOS-B (Piceance Basin)				
(II) 40 Kt, 640 Acres 10 BCF gas in-place	3.8	38	5.5	55
MESAVERDE (Piceance Basin)				
(III) 100 Kt, 640 Acres 50 BCF gas in-place	21.6	43	30.0	60
(IV) 100 Kt, 640 Acres 100 BCF gas in-place	43.0	43	58.6	59
MESAVERDE (San Juan Basin)				
100 Kt, 640 Acres 16 BCF gas in place	8.0	50	10.1	63
[Conventional: two wells, each 320 acres, 16 BCF gas in place]			[1.1]	[7]

* Based on $C_f \approx 3$ (low) and $C_f \approx 7$ (high)

** BCF=1,000 MMCF = 1 Billion Standard Cubic Feet

Table 3.2--Gas-Well-Deliverability in MCFD*

	Deliverability			
	Initial Stabilized		Average Production	
	low**	high**	low**	high**
PICTURED CLIFFS (San Juan Basin)				
(I) 10 Kt, 160 Acres, 20 years	1560	2580	480	510
10 Kt, 640 Acres, 20 years	1180	1650	840	1060
30 Kt, 640 Acres, 20 years	1360	2000	930	1200
MANCO S-B(Piceance Basin)				
(II) 40 Kt, 640 Acres, 20 years	1000	2800	550	750
MESAVERDE (Piceance Basin)				
(III) 100 Kt, 640 Acres, 50 years	4000	5000	1200	1600
(IV) 100 Kt, 640 Acres, 50 years	5000	5000	2300	3200
MESAVERDE (San Juan Basin)				
100 Kt, 640 Acres, 20 years	2000	3600	1100	1400

* MCFD = 1000 Standard Cubic Feet per Day

** Based on $C_f \approx 3$ (low) and $C_f \approx 7$ (high)

be $7,200 per well per year* [e.g., source 17], and the "net revenue" is discounted to present worth at a 6 per cent rate, assuming that revenue is collected around the end of the year. The 6 per cent rate was chosen as a minimum internal discount rate for gas companies in risk-free investments. In the early stages of a new technique, a 10 per cent rate would be more likely in projects of this nature [51, p. 9]. The 6 per cent rate allows for minimum opportunity costs a gas company would incur in risk-free investments.** (See Tables 3.3 to 3.6 .)

The net dollar value of the productions of Cases I to IV is then compared in summaries 1 and 2 to present costs and (potentially lower) future costs of nuclear well stimulation. All of the following tables are derived from data in [5, 10, 15, 16, 17, 28, 51] [Roman numerals indicate Case I, Case II, Case III and Case IV]. The built-in assumptions in the figures differ widely from case to case. The depth of emplacement, for example, ranges from 2,700 feet to 7,500 feet, the permeability and porosity are somewhat different in each formation, and with increasing depth the potential gas pressure differential is increased. None of the four cases would produce economically with present techniques. Therefore the following tables have to be read with some reservations (all based on radial, two-dimensional, unsteady-state flow models except Case I, which is based on a steady-state flow model and Figure 3.3):

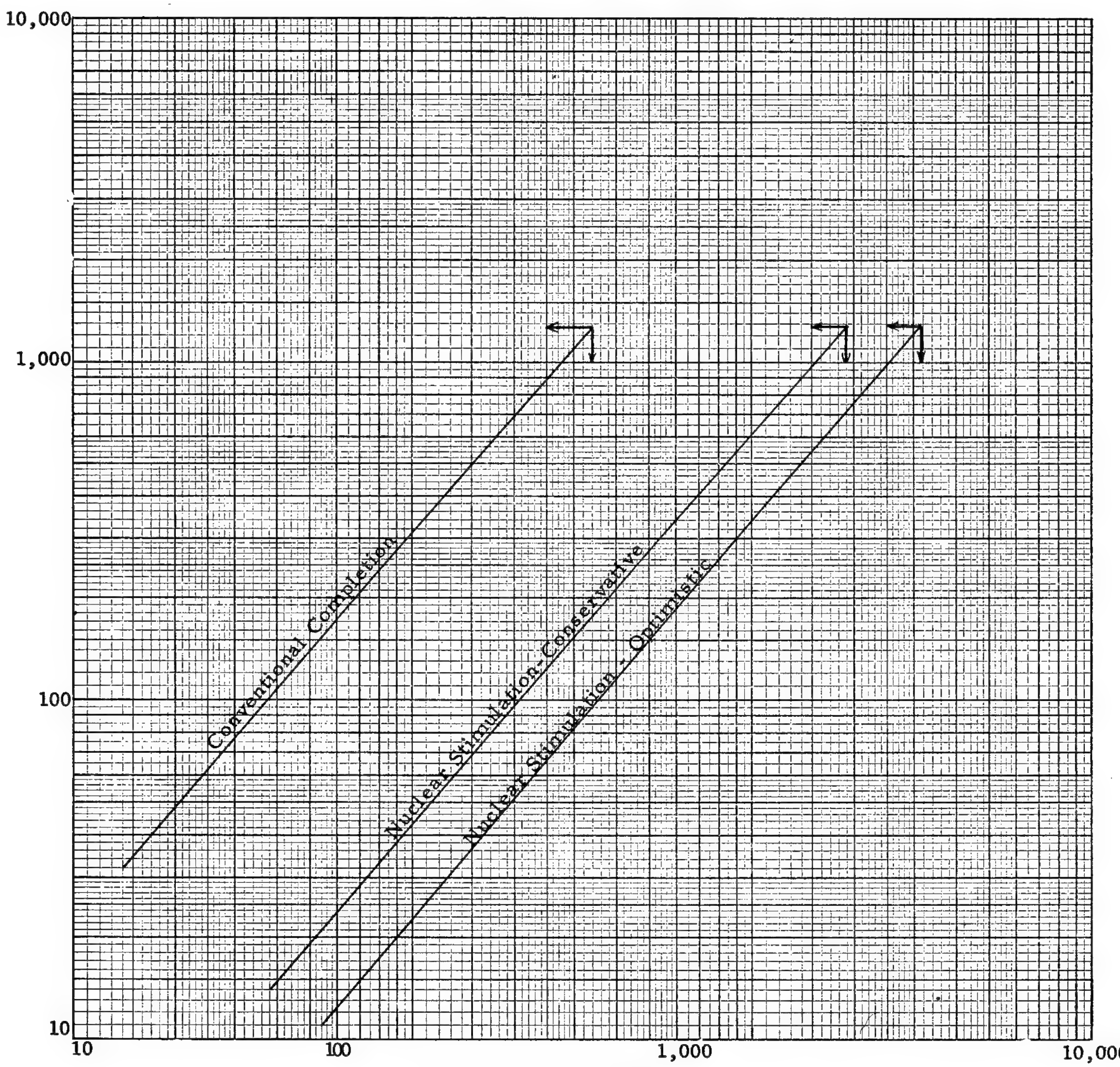
---

* A relatively high figure. Operational costs per nuclear well may be much lower.

** Gas transmission companies are restricted to a profit rate of about 6 per cent per year.

Figure 3.3--Deliverability in MCFD,* 10 KT, Device

Case I - Project Gasbuggy



Deliverability, MCFD

Original Wellhead Shut-in Pressure - 1132 psia

Wellhead Potentials: Conventional - 340 Mcf/D

Nuclear Stimulation: Conservative - 1900 Mcf/D; Optimistic - 3130 Mcf/D

* MCFD = 1000 Standard Cubic Feet per Day

** $(Pc)^2-(Pe)^2$ (in Thousands) $psia^2$

SOURCE: C. E. R. Geonuclear Corporation, Austral Oil Company, "Project Rulison Feasibility Study," 1966.

Table 3.3--Case I

10 KT, 160 acres, ≈ 5 BCF gas-in-place, 20 years, operations costs per year 7,200$, 6% discount rate

Years	Expected gas production in M^2 CF		Gross $ Income		Net $ Income		Net Discounted Income	
	low	high	low	high	low	high	low	high
1-5	960	960	144,000	144,000	108,000	108,000	90,700	90,700
6-10	960	960	144,000	144,000	108,000	108,000	67,800	67,800
11-15	954	960	143,000	144,000	107,000	108,000	50,200	50,600
16-20	646	868	97,000	130,000	61,000	94,000	21,400	32,900
	3,520	3,748	528,000	562,000	384,000	418,000	230,100	242,000

SOURCE: Based on "Project Gasbuggy," Feasibility Study by the El Paso Natural Gas Company, U.S. Atomic Energy Commission, U.S. Bureau of Mines, Lawrence Radiation Laboratories, May 1965.

* Production projection by El Paso N.G. at 525 MCFD constant production rate, i.e., for a considerable time (≈ 15 years) production capacity exceeds actual production.

Table 3.4--Case II

40 KT, 640 acres, 10 BCF in-place, 20 years, operation costs/year $7,200, 6% discount rate

Years	Expected gas production in M^2 CF		Gross $ Income		Net $ Income		Net Discounted Income	
	low	high	low	high	low	high	low	high
1-5	1,210	2,700	182,000	405,000	146,000	369,000	123,000	310,000
6-10	940	1,350	142,000	203,000	106,000	167,000	67,000	105,000
11-15	860	900	129,000	135,000	93,000	99,000	44,000	46,000
16-20	540	540	81,000	81,000	45,000	45,000	16,000	16,000
	3,550	5,490	534,000	824,000	390,000	680,000	250,000	477,000

SOURCE: Based on "A Program to Evaluate the Stimulation of Natural Gas Resources by Contained Nuclear Explosions," A Proposal to the Atomic Energy Commission from the Continental Oil Company, August 1966.

Table 3.5--Case III

100 KT (2 x 50 KT), 640 acres, 50 BCF in-place, 50 years, operational costs/year \$7,200, 6%

Years	Expected gas production capacity, M^2CF		Gross \$ Income		Net \$ Income		Net Discounted Income	
	low	high	low	high	low	high	low	high
1-5	4,800	6,935	720,000	1,040,000	684,000	1,004,000	574,000	843,000
6-10	2,700	4,640	405,000	696,000	369,000	660,000	232,000	414,000
11-15	2,400	3,400	360,000	510,000	324,000	474,000	152,000	222,000
16-20	2,400	3,400	360,000	510,000	324,000	474,000	173,000	166,000
21-25	1,750	2,250	263,000	338,000	227,000	302,000	59,000	79,000
26-30	1,750	2,250	262,000	337,000	276,000	301,000	44,000	59,000
31-35	1,600	2,000	240,000	300,000	204,000	264,000	30,000	39,000
36-40	1,600	2,000	240,000	300,000	204,000	264,000	22,000	29,000
41-45	1,300	1,350	195,000	203,000	159,000	167,000	13,000	14,000
46-50	1,300	1,350	195,000	202,000	159,000	166,000	10,000	10,000
	21,600	29,575	3,240,000	4,436,000	2,880,000	4,076,000	1,249,000	1,875,000

SOURCE: Based on Knutson, C.F., Spiess, E.R., Coats, O.R., Rulison Field Report, CER Geonuclear Corporation, January 7, 1966.

Private communication regarding Rulison Field Report.

Table 3.6--Case IV

100 KT (2 x 50 KT), 640 acres, 100 BCF gas-in-place, 50 years, operational costs/year $7,200, 6% discount rate

Years	Expected gas production capacity, M^2CF		Gross $ Income		Net $ Income		Net Discounted Income	
	low	high	low	high	low	high	low	high
1-5	8,235	9,175	1,235,000	1,376,000	1,199,000	1,340,000	1,007,000	1,125,000
6-10	6,000	9,175	900,000	1,376,000	864,000	1,340,000	542,000	841,000
11-15	4,900	8,770	735,000	1,316,000	699,000	1,280,000	328,000	600,000
16-20	4,900	8,000	735,000	1,200,000	699,000	1,164,000	245,000	408,000
21-25	3,900	5,000	585,000	750,000	549,000	714,000	144,000	187,000
26-30	3,900	5,000	585,000	750,000	549,000	714,000	107,000	140,000
31-35	3,300	4,000	495,000	600,000	459,000	564,000	67,000	82,000
36-40	3,300	4,000	495,000	600,000	459,000	564,000	50,000	62,000
41-45	2,300	2,750	345,000	413,000	309,000	377,000	25,000	31,000
	43,035	58,620	6,655,000	8,793,000	6,295,000	8,433,000	2,534,000	3,499,000

SOURCE: Based on Knutson, C.F., Spiess, E.R., Coats, O.R., Rulison Field Report, CER Geonuclear Corporation, January 7, 1966.

Private communication regarding Rulison Field Report.

The potential royalties to the Federal Government are 12.5 per cent of the gross-production value. In the Rocky Mountain area up to 90 per cent of the prospective gas-producing area is government owned, thereby giving rise to royalty payments. With the stated production figures, the following royalties would accrue:

12.5 per cent royalties

	Sum of Annual Amounts		Discounted at 6 per cent	
	low	high	low	high
Case I	$ 66,000	$ 70,000	$ 31,000	$ 32,000
Case II	$ 67,000	$ 103,000	$ 33,000	$ 62,000
Case III	$405,000	$ 554,000	$227,000	$306,000
Case IV	$832,000	$1,100,000	$338,000	$508,000

The treatment of royalties and taxes on profits when establishing <u>real</u> costs is at least controversial. The most consistent way to treat such items is to record them as side payments funded out of profits. Of course, taxes and royalties are expenses to the entrepreneur. But the inclusion of taxes on profits and royalties as costs (and for that matter of subsidies as revenues) can lead to serious misallocations of national resources, in addition to theoretical inconsistencies when making economic evaluations. A further revenue would accrue to the Federal Government through income tax levied on the (potential) profits (48 per cent). As large amounts of the gas-in-place would, without nuclear stimulation, never be produced by techniques now available, we may regard these revenues as net additions to Federal revenue.

The discounted net income would then have to cover the following initial investment costs in commercial applications:

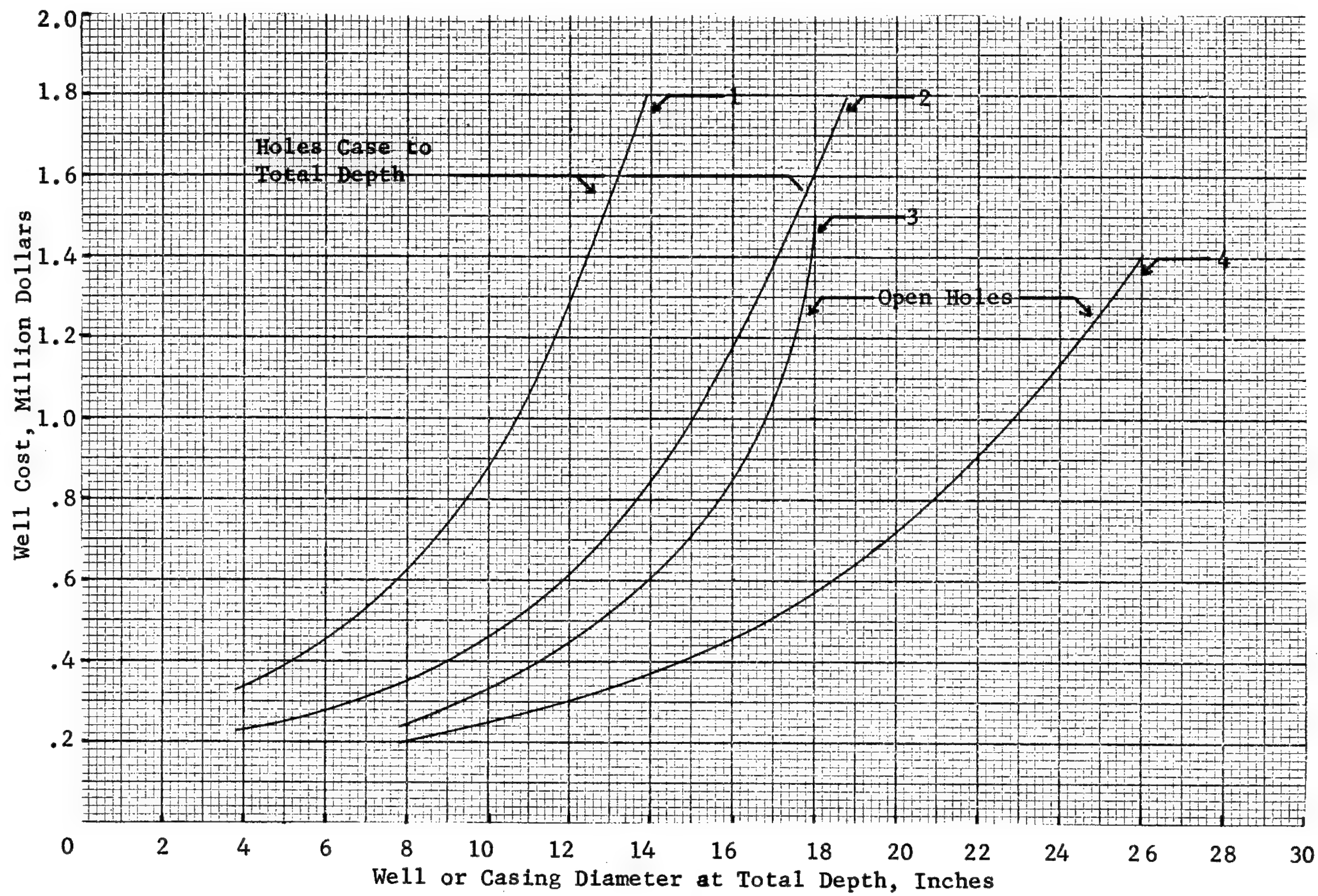
a) The costs of the device (see Figure 3.1), [51, p. 15] at projected charges for nuclear explosives. The projected charges published so far by the AEC for experimental shots are [45, p. 7]

10 KT	$350,000
20 KT	$385,000
50 KT	$425,000
100 KT	$460,000
1000 KT	$570,000
2000 KT	$600,000

These charges cover nuclear materials, fabrication and assembly, arming and firing services. Not covered by these charges are safety studies, site preparation, including construction of holes, transportation, and emplacement of devices, and support. These latter costs depend significantly on the number of explosives detonated at a given site and time. The long-run prices for nuclear explosives in commercial applications will depend on many factors. What price ranges one should expect is difficult to say now. For the long range of gas stimulation no figure for device costs can now be established. Therefore the device costs were not included in Summary 2.

b) Drilling costs for the emplacement hole at present, are a main part of the costs in nuclear stimulation. Many of the tight formations in the Rocky Mountain area do reach to 10,000 feet. These drilling costs are in general a function of the depth of emplacement, the diameter of the hole and the hardness of the rock. Figure 3.4 gives an estimate of these costs in Rocky Mountain areas [51, p. 17]. To realize the full potential benefits of nuclear stimulation at such depths, it would be desirable to

Figure 3.4--Emplacement Costs Versus Diameter Size of Nuclear Explosive



All Curves: Total Depth = 10,000'
Surface Casing to 1000'
No Severe Lost Circulation
No Testing, Usual Logging
Curves 1 and 3: Intermediate Casing to 7000'
Curves 2 and 4: No Intermediate Casing

restrict the diameter of the explosives up to 500 KT yield to a maximum of 12-18 inches. There are indications that considerable progress is possible (i.e., below the diameters shown in previous Figure 3.1, [51, p. 15]). In our four cases the (present) emplacement costs are estimated to be

Case I	4,150 feet	10 KT diameter	\$200,000
Case II	2,700 feet	40 KT diameter	\$150,000
Case III	7,500 feet	50 KT diameter	\$600,000
Case IV	7,500 feet	50 KT diameter	\$600,000

Cases III and IV demonstrate one possible way to lower emplacement costs, i.e., by a simultaneous, vertical emplacement of two devices. In formations where vertical connection of more gas-layers is called for, such an emplacement might prove to be more economic than a single, higher-yield shot. There exist, however, at present costs a trade-off between lower emplacement costs when two devices (of smaller diameter) are used and the lower cost of one single device with similar total yield (\$850,000 vs \$460,000 in case of 2 x 50 KT and one 100 KT shot). After the explosion has been set off, re-entry wells (=production wells) have to be drilled. Whether the existing emplacement well could sometimes be utilized (and to which extent) is uncertain. Reentry wells are normal gas production wells and their costs are those generally anticipated in the gas industry. In addition, the depth of the re-entry wells would be somewhat less than the original emplacement well (by about the height of the chimney above shot point). At depths to 10,000 feet these re-entry wells should cost about \$150-200,000. In the four cases, re-entry well costs are estimated as follows:

Case I	$150,000*
Case II	$100,000
Case III	$280,000
Case IV	$280,000

c) Miscellaneous other costs [51, 10, 16, 17].

Given the present uncertainties as to how much of the initial gas will be tritiated and to what extent this will pose a problem, it is difficult to attach any specific cost figure for detritiation of the gas. It may turn out that the contamination of the gas can be held to a very low level or avoided altogether. On the other hand, a substantial part of the gas might be seriously contaminated and a variety of proposals exist to deal with this particular decontamination problem. The costs of each procedure differ and are in some cases not even known. Present opinions in this field are too divergent to allow any particular cost estimate. However, there exist enough reasons to expect that the cost of decontamination can be held low. The uncertainty regarding the extent of tritiation is one main area which could adequately be assessed by experiments in nuclear stimulation.

Other costs occur in large scale commercial operations [51, p. 14 among others]. Allowance has to be made for engineering and inspection costs, miscellaneous construction costs, well testing, communciations, other support operations and finally, the industrial safety program. In large scale applications, of nuclear explosives of the same yield and the same formation, these miscellaneous costs might be held to $100,000 per well. Donald Edwards, Director of Safety Evaluation Division at the

* Normal Pictured Cliffs wells cost about $40,000. Thus our estimated costs are somewhat conservative.

Nevada Operations Office estimated the average safety costs in nuclear explosive experiments to amount to about $500,000 per experiment in the 10 KT to 20 KT range (single, off-site experiments). This figure has to a large extent a fixed cost character and does not increase appreciably with the increase in the yield of the explosive. In repetitive, commercial applications, one-and-the-same kind of device, this cost figure would be below $100,000 per explosion. A substantial part of this cost figure goes into labor costs for personnel employed in each experimental shot. Another substantial part goes for instrumentation. Safety aspects in Plowshare are extensively discussed in Chapter 4 of the General Report on Plowshare by MATHEMATICA. In the case of gas stimulation, volatile nuclides seem to pose the most serious problem. Given their nature, volatile nuclides will readily intermingle with the gas itself and in addition the neutron fluxes produced by either fission or fusion explosions will activate amounts of the hydrogen present in the hydrocarbons surrounding the shot point.

Flaring (venting) of two, or more, chimney volumes of gas should remove about 95% of the contaminants present in the well and not trapped in the glass melt at the bottom of the chimney. If flaring or dumping an initial part of the product is planned, great care would be required to reduce the stack (flare) effluent to be consistent with MPC (= Maximum Permissible Concentration) values.

Within the chimney itself, tritium is expected to occur at as high a rate as 0.04 microcuries per cubic cm. [13]. By venting, the contamination of the remaining gas could be lowered by a factor of 10 or more. Dilution

with uncontaminated gas would then yield gas which would satisfy safety requirements.

The tritiation problem becomes complicated by the uncertainty with regard to the amount of tritiation of hydrogen in the surrounding hydrocarbons and water [125, 154, et al.]. Research in this area is in progress [58]. Experiments in gas and water containing formations are necessary for further knowledge and accurate evaluation. Through device design and emplacement techniques, tritiation could possibly be minimized if not eliminated. Refractory nuclides are expected to be less of a problem in gas stimulation, which would indicate some advantage in using fission devices, and if by any chance refractory particles do occur at the well head, they could be easily separated from the gas itself.

For purposes of this study, safety costs are estimated to amount to another $100, 000, giving overall miscelleous costs of about $200, 000. Operational costs of the wells were included earlier.

The above results are collected in Summaries 1 and 2 and in Figure 3.5. At present costs and a 6 per cent internal discount rate, high production in Case III nearly yields a break-even; in both high and low productions of Case IV a considerable profit is realized in excess of the 6 per cent. In Case III there are 50 BCF underground at 7, 500 feet: this case would be in the neighborhood of a 6 per cent profitability given all the particular characteristics of this experiment. This rate of return is slightly exceeded if in the same field 100 BCF are present and a relatively low increase in permeability occurs. If all the optimistic estimates are realized, a high payoff is to be expected in Case IV, even if royalties have to be paid (Case III is still uneconomic if substantial royalties are to be paid).

Table 3.7--(1) Summary of Cases I to IV at Present Costs

	Total Net Income, i.e., 0% Discount		Present Worth of Net Income, 6% discount Rate		Costs of Devices	Costs of emplacement	Miscellaneous Costs
	low	high	low	high			
Case I	384,000	418,000	230,000	240,000	350,000	200,000	200,000
Case II	390,000	680,000	250,000	480,000	410,000	150,000	200,000
Case III	2,880,000	4,076,000	1,250,000	1,880,000	850,000	600,000	200,000
Case IV	6,295,000	8,433,000	2,534,000	3,499,000	850,000	600,000	200,000

	Costs of re-entry well	Balance Over Total Net Income, 0% discount Rate		Balance Over Discounted Net Income, 6%		Potential Royalties to Federal Government, Discounted at 6%	
		low	high	low	high	low	high
Case I	150,000	-516,000	-482,000	-670,000	-660,000	31,000	32,000
Case II	100,000	-470,000	-180,000	-610,000	-380,000	33,000	62,000
Case III	280,000	+950,000	+2,146,000	-680,000	-50,000	227,000	306,000
Case IV	280,000	+4,365,000	+6,500,000	+604,000	+1,570,000	388,000	508,000

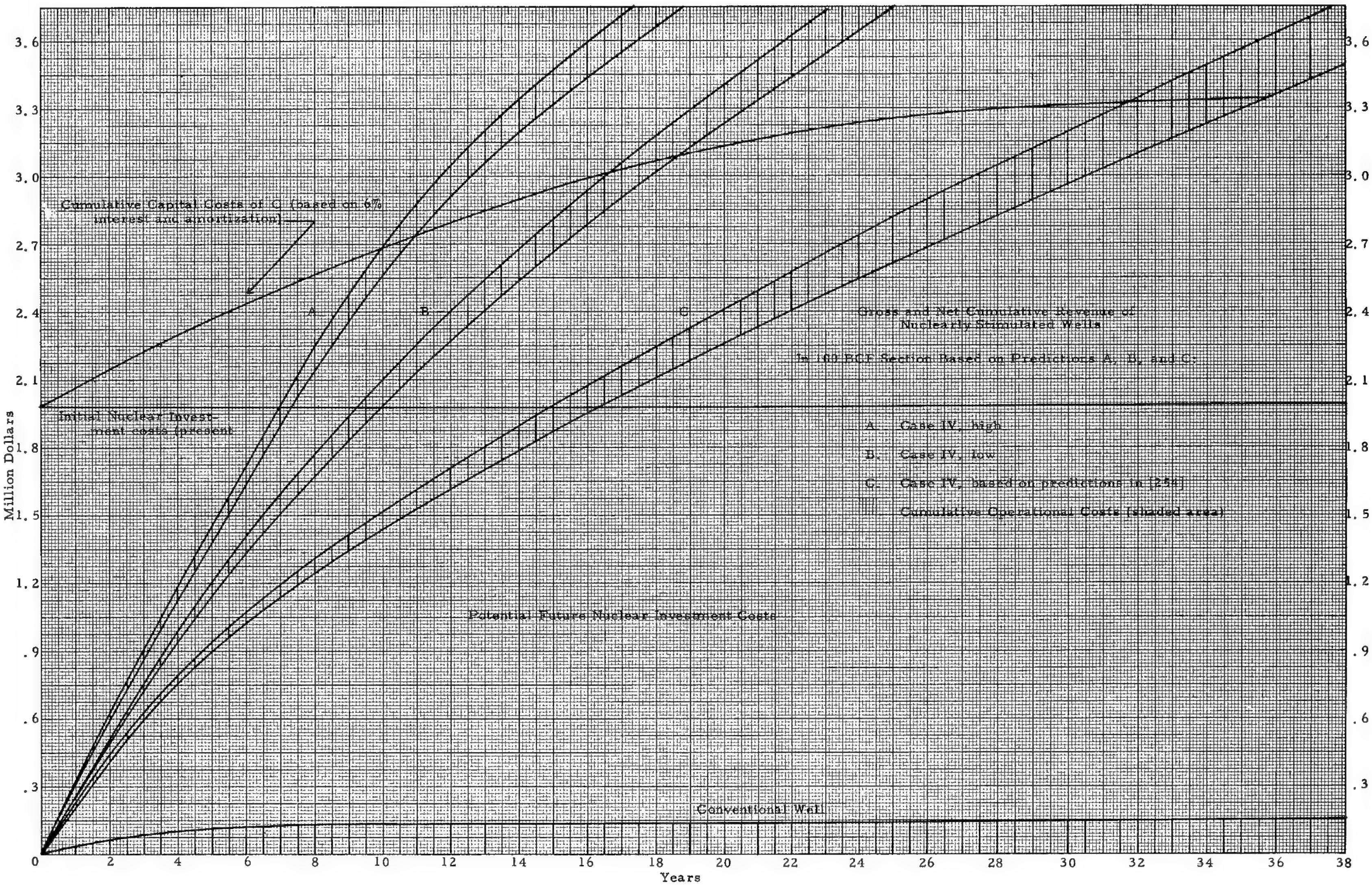
Table 3.8--(2) Summary of Cases I to IV at Potential Long Range Costs, Excluding Costs of Device

	Total Net Income 0% Discount Rate		Present Worth of Net Income, 6% Discount Rate		Costs of Emplacement	Costs of Re-entry Well	Miscellaneous Costs
	low	high	low	high			
Case I	384,000	418,000	230,000	240,000	150,000	(150,000)	100,000
Case II	390,000	680,000	250,000	480,000	100,000	(100,000)	100,000
Case III	2,880,000	4,076,000	1,250,000	1,880,000	280,000	(280,000)	100,000
Case IV	6,295,000	8,433,000	2,534,000	3,499,000	280,000	(280,000)	100,000

Cont'd	Balance Over Income,* 0%	Total Net	Balance Over Present Net Worth*, 6%	
	low	high	low	high
Case I	-16,000	+18,000	-170,000	-160,000
Case II	+90,000	+380,000	-50,000	+180,000
Case III	2,220,000	3,416,000	590,000	1,220,000
Case IV	5,635,000	7,773,000	1,874,000	2,839,000

* Costs of device not included.

Figure 3. 5


Cumulative Capital Costs of C (based on 6%
interest and amortization)
Initial Nuclear Invest-
ment costs (present
A
B
C
Gross and Net Cumulative Revenue of
Nuclearly Stimulated Wells
In 100 BCF Section Based on Predictions A, B, and C:
A. Case IV, high
B. Case IV, low
C. Case IV, based on predictions in [25]
Cumulative Operational Costs (shaded area)
Potential Future Nuclear Investment Costs
Conventional Well
Million Dollars
Years
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
.3
.6
.9
1.2
1.5
1.8
2.1
2.4
2.7
3.0
3.3
3.6

If long run cost reductions are realized (Summary 2), it might be economically feasible for tight fields down to 10 BCF of gas to be stimulated by nuclear methods. Case III would exceed 6 per cent profitability considerably, even after the deduction of potential royalties. Figure 3.5 shows the cumulative gross income of Case IV under different predicted gas flows, the operating costs per well (shaded areas) and the cumulative net income; the present initial investment costs for Case IV are shown with $1.9 million and the cumulative capital costs were calculated on the basis of 6% p.a. interest and the amortization of the capital by the net income flow for Case IV-C, the lowest prediction shown in Figure 3.5 , based on gas flow predictions in [254]. Case IV-C has an effective rate of return of slightly more than 6%, Case IV-B an effective rate of return of 9% and Case IV-A, the most optimistic prediction, a rate of less than 15%, based on gas flow of at least 30 years.

A conventional well would be uneconomic in this formation in any case, as the revenues from such a well do not even suffice to cover operating costs. Thus, at present initial investment costs , there do exist tight natural gas formations which are not economically productive with conventional techniques and which by nuclear stimulation would produce a considerable amount of natural gas at some positive rate of return, perhaps as high as 15%.

However, from the above analyses, and Figure 3.5 , it is also evident that initial investment costs do play a decisive role in determining whether a certain gas formation can be stimulated economically.

Only a slight change in interest rates, or a relatively minor increase in investment costs would exclude many potential tight gas formations from

nuclear stimulation. One important parameter will be the estimated quantity of gas in place, as shown in Figure 3.5.

Another, equally important parameter will be the ultimate required initial investment for nuclear stimulation which again brings on a set of various potential developments: a reduction of the required diameter of nuclear explosives for gas stimulation, whether and to which extent the emplacement hole can be used as re-entry well, the long run charges for nuclear explosives in commercial applications and, also, the diminuation of some existing uncertainties as to the effective stimulation of gas formations by such explosions. This will require a number of carefully planned experiments.

One tentative estimate of such a long run initial investment is shown in Figure 3.5, based on potential long range costs shown in Table 3.8 including somewhat reduced charges for the nuclear explosives. At this reduced initial investment cost, all cases shown in Figure 3.5 would be economic with a considerable rate of return. Another potential procedure would be to calculate for each formation upper limits to the charges for nuclear explosives under which that formation could still be recovered economically at some agreed upon rate of return. At present, however, the uncertainties on predicted gas flows from nuclearly stimulated gas wells are yet such as to make any calculation of this kind very difficult. Again, empirical knowledge through experiments is needed.

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